

Mars Tumbleweed: FY2003 Conceptual Design Assessment

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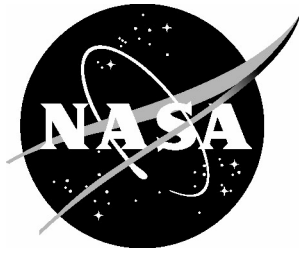
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1. Introduction

1.1. Background

NASA Langley Research Center (LaRC) is studying concepts for a new type of “rover” vehicle that would be propelled by the wind (fig. 1). Known as a Mars “Tumbleweed,” it would derive mobility through use of the Martian surface winds. Tumbleweeds could conceivably travel greater distances, cover larger areas of the surface, and provide access to areas inaccessible by conventional rovers. They would be lightweight and relatively inexpensive, allowing a multiple vehicle network to be deployed on a single mission. Tumbleweed rovers would be equipped with microelectronic sensors for conducting science and serve as scouts—searching broad areas to identify specific locations for follow-on investigation by other explorers (fig. 2).

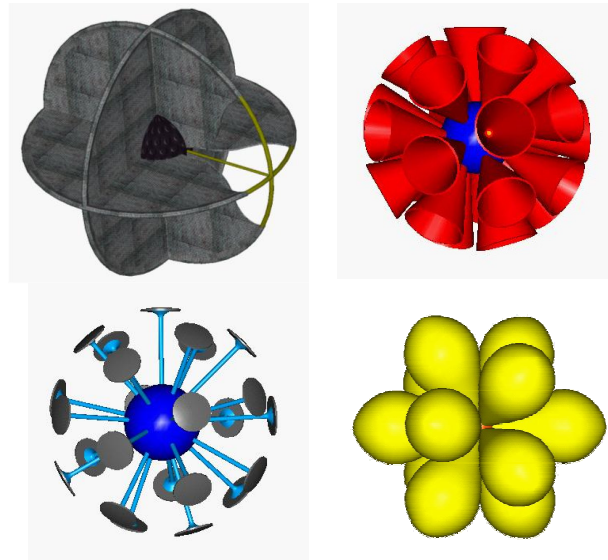


Figure 1. NASA LaRC Tumbleweed concepts (clockwise from top left) Box Kite, Tumblecup, Wedges, and Dandelion.

A deployed Tumbleweed would be approximately 4 to 6 m in diameter and have a mass of approximately 10 to 20 kg, including the science instrument complement and supporting subsystems of structures, power, communication, and navigation.

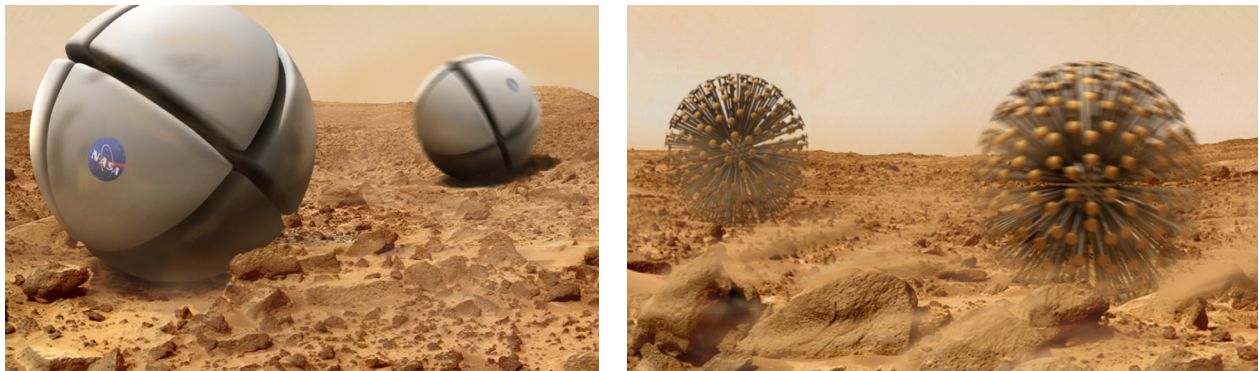


Figure 2. Artist depictions of the Wedges and Dandelion concepts on Mars.

1.2. Goals of 2003 Study

Preliminary assessments of LaRC Tumbleweed concepts were conducted in Fiscal Year (FY) 2002 (ref. 1). An extensive investigation was planned for FY03, with the following goals:

- Refine the science objectives and develop a candidate mission scenario.
- Define supporting subsystem capabilities and assess technologies.
 - Structures/Materials
 - Power
 - Communications
- Conduct wind tunnel testing to determine drag characteristics of concepts.
- Develop a dynamic simulation capability to assess rolling, bouncing characteristics.
- Collaborate with universities to study Tumbleweed concepts.
- Provide outreach presentations to the general public.

The following sections provide a summary of the accomplishments within these areas.

2. Science Objectives

2.1. Review of MEPAG Goals

The goals and objectives defined by the Mars Exploration Program Advisory Group (MEPAG) (ref. 2) were examined in the FY02 Tumbleweed study:

- Determine whether life ever arose on Mars.
- Determine climate on Mars.
- Determine the evolution of the surface and interior of Mars—“geology.”

A subset of the MEPAG objectives (within these goals) that a Tumbleweed rover potentially could perform was identified. These objectives were tabulated along with the associated measurements and related instruments. The level of controllability (e.g., stop/start) needed by the Tumbleweed to accomplish the measurements was also assessed and identified.

In FY03, the subset of MEPAG science objectives was reexamined, including an extensive literature review and discussions with scientists and engineers at NASA LaRC and elsewhere that are involved in instrumentation development for Mars exploration. As a result, the “Search for Life” goal was identified as the most scientifically interesting and challenging mission for the Tumbleweed concept. In this role, Tumbleweed rovers would serve as in situ scouts, surveying vast areas of the planet’s surface to locate areas of interest for follow-on, comprehensive surveys by future landers, rovers, or perhaps human explorers.

2.2. Tumbleweed Science Objectives Based on MEPAG Goals

Table 1 summarizes the objectives, investigations, and measurements within the MEPAG “Search for Life” goal that Mars Tumbleweed rovers could potentially conduct. The table also includes associated instrumentation. A detailed table in appendix A provides mass, power, and data estimates of existing or planned near-term instruments that correspond to the example instrumentation. This table only provides a representative instrumentation set and is not intended to be all-inclusive. Specific science mission objectives, along with an associated instrument complement, will need to be identified by a science definition team.

Table 1. MEPAG Search for Life Goal:
Objectives, Investigations, Measurements, and Example Instruments for Tumbleweed

MEPAG objective/ investigation	MEPAG measurement	Example instrumentation
Determine whether life exists today— <i>Carry out in situ exploration of areas suspected of harboring liquid water.</i>	For at least 20 stations at 4 targeted sites, conduct <i>in situ</i> geophysical and chemical searches for subsurface water and other volatiles over km ² surface.	Water vapor sensors
		Gas chromatograph/mass spectrometer
Assess the extent of prebiotic organic chemical evolution— <i>Search for complex organic molecules in rocks and soils.</i>	In situ/mobile platforms deployed to at least 3 well-characterized and diverse sites to assess the mineralogy,...	X-ray diffraction
		X-ray fluorescence
		Laser Raman spectrometer
		Mossbauer spectrometer
	geochemistry, and ...	Mini-thermal emission spectrometer (TES)
		Alpha proton X-ray spectrometer
	organic materials	Mini-Mass spectrometer
		Gas chromatograph/mass spectrometer
Visual observations for life.	Imaging	Laser desorption spectroscopy
		Panoramic stereo camera
		Imager for Mars Pathfinder

2.3. Preliminary Mission Concept

The current Mars program strategy in the search for life is to “follow the water”; however, many sites on Mars that may harbor water and are scientifically interesting are not accessible by conventional robotic systems, partially due to the high winds associated with these areas. Mark Richardson, a Caltech Mars meteorologist, is quoted in the March 2, 2003 edition of the Los Angeles Times, “The planet’s most interesting places tend to be associated with scary winds.”

An area of particular scientific interest is the gullies that have been observed in photographs (fig. 3) taken by the Mars Global Surveyor (ref. 3). There is much speculation regarding the origin of these features, including subsurface aquifers, melting snow packs, carbon dioxide outbursts, and dry dust flows (ref. 4). Current conventional rover designs would have difficulty accessing these features; however, a Tumbleweed vehicle could potentially be made to roll down the gullies or examine regions below the gullies within canyons and craters.



Figure 3. Gullies in Newton Basin (NASA/JPL/Malin Space Science Systems).

To investigate gullies, Tumbleweed rovers could be deployed at the entrance to a valley or canyon that exhibits these features and allowed to be driven into the region by the wind. Alternatively, Tumbleweeds could be deployed near the top of a valley, canyon, or crater and be blown by the wind down the slopes into the area of interest. The Tumbleweed would serve as a scout in these areas, searching for water vapor and traces of biogenic gases.

3. System Definition

3.1. Overview of Design Challenges

Development of a lightweight system is important for a robust Tumbleweed capable of operating in the low density atmosphere of Mars. Lightweight structures and materials will be needed as well as lightweight subsystems for power, communications, and deployment.

3.2. Structures and Materials

The structural system for the Mars Tumbleweed must provide the core support and maintain the correct shape for roving while supporting the other subsystems and protecting the science instrument core from permanent damage. The entire tumbleweed rover must be packaged such that it could be carried as a secondary payload on a Mars mission but still deploy into the final shape large enough to propel itself in the Martian winds. It will serve as the main frame to attach the wind-capturing devices and hold the correct shape to offer better rolling and maneuverability. Science instruments will be carried in an inner core that must be protected by the structure during expected high-speed impacts. Portions of the structure may be considered multifunctional, as they may carry out other system operations such as propulsion, communication, or other subsystems (as may be designed). Material selection for the tumbleweed structural systems must also allow for the high thermal gradients expected during the mission time frame and the many other environmental effects of Mars. Some environmental considerations are the rock impact tolerance and the ability to stop rips in thin films that may be used. The materials will also have to be capable of having high packing-to-deployment ratios.

To understand and design the structure for a Mars Tumbleweed rover, a two-dimensional (2-D) representation of the rover was created and simulated during high loads. The 2-D model was chosen to best characterize the behavior and be able to more easily compare the various Tumbleweed concepts. The present designs were modeled as a central core payload mass in the center of a hoop connected by either tension or compression elements. The highest expected loads occur during impact, either from deployment or from tumbling across the Martian surface. The nonlinear impact analysis program, LS-DYNA-3D, was used to study the impacts of the rover concepts. Dr. Chris White from JPL created the models and presented the results by assuming a 20-m/s impact speed into a rigid planar surface at a 45° angle. Trend lines were created by assuming different payload masses and hoop and spoke sizes. The tension spoke cases provided the best results, while the compression spokes were very dependent on orientation of the spoke to the ground. Different methods were used to better quantify the beam spoke analysis, but the coupling of the orientation and deflection proved to be difficult to overcome. The results do show promising trends when using the tension spoke and give insight into how the beam spoke versions will behave under impact. Additional analyses will be conducted in FY04.

3.3. Power

A preliminary review of power source considerations for Mars Tumbleweed was conducted and several potential power systems were compared (table 2). The advantages and disadvantages of the power system concepts were defined in relation to system drivers and mission parameters; however, a detailed trade study is needed to identify the best power source for each tumbleweed design configuration. The results of this preliminary assessment indicate that while solar arrays are a very reliable power source for conventional rover designs, radioisotope power sources provide a greater range of power capabilities and continuous power over a long period of time. Thus, they may be more applicable to a Tumbleweed vehicle. The technologies in table 2 are discussed in the following sections.

Table 2. Power System Options

Technology	Power	Advantage	Disadvantage
Photovoltaic solar arrays	>10 W	- Low Mass - High TRL	- Durability - Limited range (day cycles, shadowing effects, etc.)
Primary batteries	>10 W	- Low mass - No need for thermal control - Easy to package - High TRL - Durability	- Low life time - Limited in power (without impacting mass)
(RTPV) Radioisotope Thermophotovoltaic	10 to 75 W	- Attractive alpha	- Radioactive material - High radiator temps - Need unobstructed view (for cooling) - Low efficiency - Low TRL
RHU milliwatt radioisotope	40 mW at 4-percent efficiency	- Low mass - Durability	- Radioactive material
Thermoelectric	1 to 20 W	- Can be achieved within the mission time frame - Manageable thermal control - Durability	- Radioactive material

3.3.1. Solar Power

The use of solar power as a potential power source for Tumbleweed is a primary option. Solar arrays have been a reliable source of power for the recent Mars surface exploration missions, Mars Pathfinder, and Mars Exploration Rovers. Although the design and structure of Tumbleweed have yet to be determined, several configurations being explored could easily accommodate solar array power, including the Wedges and Box Kite designs, which offer sufficient surface area to accommodate solar panels. Configurations such as the Dandelion or Tumblecup do not easily lend themselves to solar array placement. For the use of solar arrays on such designs, complex deployable systems may be necessary, but would be an undesired complexity that could greatly affect anticipated mass requirements and overall performance.

An overall disadvantage of solar arrays on Tumbleweed results from the rolling motion of Tumbleweed. Conventional Mars rovers use solar power because the Sun easily illuminates the fixed arrays. The rolling Tumbleweed, based on the spherical shape, has, at a maximum, only one half its potential illumination area available at any one time. Solar arrays would therefore need to encompass the entire Tumbleweed and be well positioned for maximum solar radiation. Additional mass associated with this “blanket” of solar cells may be detrimental to mass constraints. Additionally, while the Box Kite design provides greater surface area to accommodate the arrays, the orthogonal panels may also cause unwanted shading of panels, which would further decrease available energy based on solar zenith angles.

Further disadvantages exist because of the accumulated dust in the atmosphere. The dusty environment of Mars decreases solar flux and also covers solar array panels. For this reason, prior missions were planned to last only 90 days due to dust accumulation on solar panels and the resultant lack of power. Data from previous missions show an average decrease in available power of 0.3 percent per day, which equates to a 25-percent power deficiency after only 96 days. Although the Tumbleweed is expected to roll, it is unknown whether this rolling will remove or possibly increase dust accumulation on the solar panels. And finally, disadvantages exist for potential exploration sites. As discussed in section 2.0, many scientifically interesting sites may be located in canyons and craters. These environments would prevent direct solar flux for a large part of the day, significantly reducing the available energy.

3.3.2. Primary Batteries

Nonrechargeable batteries are flight proven and highly reliable for short mission lifetimes. Primary batteries are typically used for high power but short duration operations. Although battery technologies, including thin-film batteries and lithium chemistries, have continually improved, the Tumbleweed long duration mission objectives do not support the use of primary batteries as the main power source. Primary batteries offer high specific energies, but power requirements for long missions increase system mass above mission constraints. The expectations for a multiyear mission for Tumbleweed greatly accommodate reusable forms of energy or nuclear power sources, which have much longer mission capabilities than primary batteries. Primary battery technology cannot provide the necessary power within Tumbleweed mass constraints to satisfy expected power requirements.

Although primary batteries are not viable solutions to Tumbleweed’s main power needs, they may be useful during the landing sequence and/or deployment. The large size of Tumbleweed requires a deployment prior to or after landing on Mars. This deployment may require power and could be initiated by primary batteries. These batteries could supply the required power for the short time segment and have little impact on the overall mass of the Tumbleweed. Thus, although primary batteries are not recognized as a chief power option, they may prove valuable for other vital aspects of the mission.

3.3.3. Radioisotope Thermophotovoltaic Systems

Radioisotope Thermophotovoltaic (RTPV) systems convert heat from General Purpose Heat Source (GPHS) modules into electrical energy by using thermophotovoltaic cells. GPHS modules have been used on radioisotope thermoelectric generators (RTG) for previous space missions including Galileo, Cassini, and Ulysses and have served as a proven continuous power source independent of solar energy. The Galileo RTG consisted of 18 GPHS modules designed for an electrical output of 285 W. GPHS modules contain plutonium (Pu-238) fuel that releases heat upon the nuclear decay of the radioisotope. This heat is converted to electrical energy for a total specific energy of over 5 W/kg.

Studies sponsored by the Department of Energy (DOE) have investigated the use of singular and fractional GPHS modules for the design of small RTPV generators. These RTPV systems would produce 20 W of electrical energy or less and could be a main power source for smaller spacecraft. Simply put, the low power RTPV systems are scaled versions of RTGs. However, photovoltaic (PV) cells of the RTPV system convert the infrared heat from nuclear decay into electrical energy as compared to the thermocouples of RTGs. Another difference for RTPV systems is the need of larger radiator fins for a lower cell temperature, which increases power output of PV cells; so a minimal cell temperature is desired. However, larger radiators needed to produce these lower temperatures may greatly increase system mass.

RTPV systems may be easily integrated into the core of several tumbleweed designs because the RTPV system power source is very compact. The inner core, which houses the radioisotope, as well as necessary shielding, is a cube with 7.6-cm sides for the 10-W design. The large radiator fins necessary for excess heat dissipation could potentially be incorporated into the Tumbleweed structure to save mass.

These experimental RTPV designs present power outputs that adequately address preliminary Tumbleweed system requirements within an acceptable mass range and offer continuous long life power, thus providing a potential viable power source for Tumbleweed. RTPV units are also more rugged and resistant to damage than solar arrays. Disadvantages of RTPV systems include cost, difficulties associated with launching nuclear power sources into space, and a low technology readiness level of 5. However, future advancements within nuclear programs, such as NASA's Prometheus project, may alleviate some of these disadvantages.

3.3.4. Milliwatt Radioisotope Power

Milliwatt Radioisotope Power Sources use Radioisotope Heater Units (RHU) as a source of thermal energy. The energy emitted from this small radioisotope source is converted to electrical energy by a small thermoelectric generator. RHUs are very small and lightweight and produce 1 W of thermal energy. They have been used in many spacecraft, including three aboard Mars Pathfinder Sojourner rover, to provide localized heating to electronics and instruments. The future Mars Scout mission PASCAL will use milliwatt radioisotope power to collect atmospheric data.

The experimental results examined the use of one and two RHUs per thermoelectric module. Efficiency and power output significantly increased with two RHUs, but increased thermoelectric properties of Mars PASCAL provide greatest efficiency at the cost of added mass. These milliwatt radioisotope power sources offer similar advantages to RTPV systems, including ruggedness and continuous power, but power output may be lower than required. Selection of milliwatt radioisotope power sources will be primarily dependent on payload power requirements.

3.3.5. Microthermoelectric Generators Systems

Similar to previously mentioned radioisotope power sources, microthermoelectric generators convert thermal energy into electrical energy. A temperature difference between the hot and cold surfaces of the thermoelectric generator causes a flow of current with power output proportional to the thermal gradient. Due to the presence of thermal gradients on Mars at night, thermoelectric generators may be a sufficient source of power for Tumbleweed. These thermal gradients exist near the surface (~3 m), lower than the expected Tumbleweed diameter, and can reach greater than 20 °K.

A disadvantage of thermoelectric generators is that heat pipes would be required to create hot and cold surfaces for maximum power output. These pipes must extend to the extremes of the thermal gradient layers and may reach 3 m, increasing the power system mass. Furthermore, the thermal gradients may not provide enough energy to exceed specific power output of other power sources. Additionally, the motion of Tumbleweed must be controllable to position thermoelectric modules for highest efficiency. Purely passive Tumbleweeds would greatly hinder the use of thermal gradients on Mars as a source of power. Many units would be required, and the scalability and networking integrations would be costly.

3.3.6. Advanced Power Systems

Several advanced power generation systems were also investigated, including piezoelectric materials, kinetic devices, flywheels, and wind turbines. Piezoelectric devices use kinetic motion to induce pressure on lead zirconate titanate (PZT) films to produce electrical energy. While they display a promising future, their current low power output and efficiency hinder near term use for a Tumbleweed power source. Kinetic devices, such as kinetic dynamos found in certain flashlights and watches, would likewise convert the kinetic motion of the Tumbleweed into useable electrical power. However, due to problems associated with the magnetic fields they generate and issues pertaining to scalable technologies, kinetic power systems do not appear feasible in the near term for Tumbleweed. Flywheels store kinetic energy in a rotating disk and offer high specific power for energy storage; however, the uncontrolled nature of a passive Tumbleweed would not provide adequate energy for efficient storage by flywheels. Wind turbines, including system implementation to ensure perpendicular wind flow to the turbine, would also be costly. Since Tumbleweed motion is dependent on surface winds, the potential of using wind turbines for power generation may also exist. However, the wind turbine would have to be independent of Tumbleweed motion to enable power storage. Thus, while advanced technologies may provide power generation while offering a mass savings, they are currently not flight proven and would require considerable development before they could be used on the Martian surface.

3.4. Communication

Communications for the Tumbleweed mission will rely on existing orbiting assets in Mars orbit(s) to provide the relays necessary for communications (fig. 4). Using Mars relay assets, the Tumbleweed communications will consist of Ultra High Frequency (UHF) communications from the surface vehicle(s) to orbiting spacecraft and will use existing formats and protocols already established for the Mars communications relays (ref. 5). The basic requirements trades for Tumbleweed communications are as follows:

- Daylight communications versus nighttime communications
- Minutes per pass; passes per day or per week
- Data rate (raw telemetry versus processed telemetry)

- Mission duration
- Multiple coverage to multiple ground vehicles
- Surface location
- Surface vehicle antenna selection (e.g., patch, dipole, helical)
- Transmit power

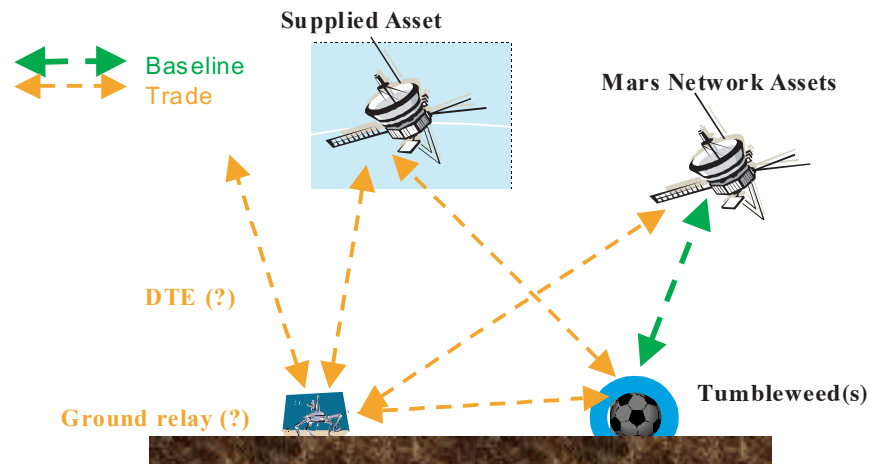


Figure 4. Mars Tumbleweed communications concept.

Each Tumbleweed vehicle will use UHF communications to transmit data to the orbiting assets when a communications opportunity exists. The use of an acknowledge and receipt protocol ensures that the data will be transmitted when a Tumbleweed establishes a link to an orbiting asset. Basic characteristics should be these:

- Radio Protocol: CCSDS Prox-1 Space link
- Full duplex, half duplex, simplex

Transmit

- 437.1 MHz; transmit power of 1 to 10 W minimum
- Data rates: Support for 2, 8, 32 kbps, minimum
- Modulation: Uncoded convolutional ($k = 7$, $R = 1/2$)
- Electra transceiver compatible

Receive

- 405.585625 MHz
- Data rates: 1 to 1024 kbps, mod 2 steps
- Modulation: $k = 7$, $R = 1/2$; Reed-Solomon (204/188 or 255/239)
- Electra transceiver compatible

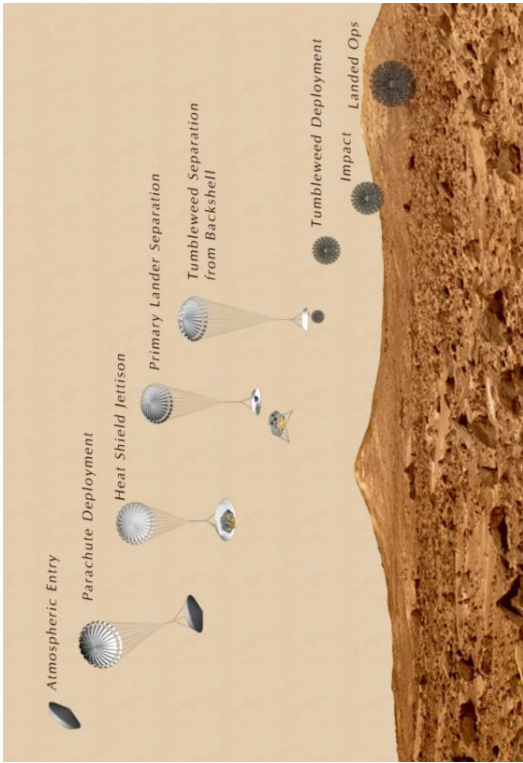
3.5. Deployment Concepts

Five concepts for deployment of Tumbleweeds onto the Martian surface have been developed (figs. 5 and 6):

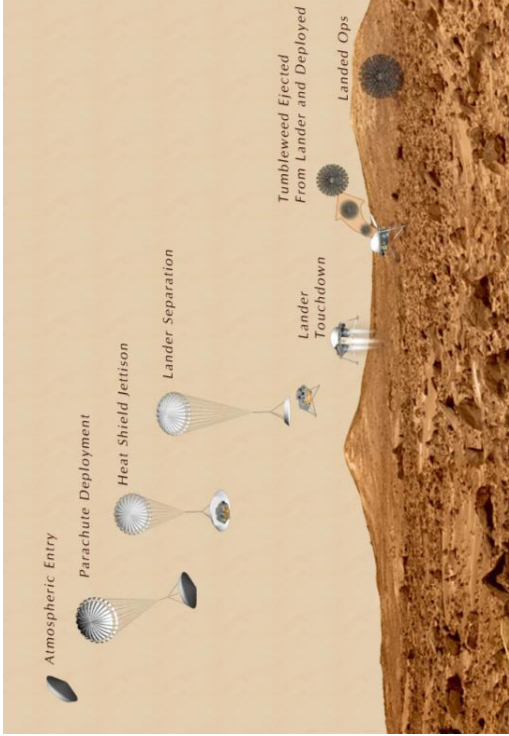
- Secondary payload on aeroshell
- Secondary payload on lander
- Secondary payload on cruise stage
- Primary payload on dedicated Tumbleweed mission—self landing
- Primary payload on dedicated Tumbleweed mission—airbag landing

The first three deployment options (fig. 5) are concepts whereby the Tumbleweed is a secondary payload, flown as a “piggyback” to a previously planned mission with available mass and volume margin. In the first deployment concept (fig. 5(a)), a Tumbleweed rover is packaged as ballast on the backshell of the entry system of a primary lander mission to provide a relatively inexpensive ride to Mars. In this scenario, the Tumbleweed is deployed at the proper time after the lander separates and is clear from the backshell. One disadvantage to this approach is that the ballast location and mass requirement for the primary mission may not match the mass properties and packaged volume of a Tumbleweed vehicle. The next deployment option (fig. 5(b)) also presents a Tumbleweed vehicle carried as a secondary payload on a lander mission; however, the Tumbleweed is attached to the lander itself rather than the backshell and is deployed after a successful touchdown and activation of lander. As with the first concept, this option also provides a relatively inexpensive “piggyback” ride to Mars; however, because of potential risks to the primary mission from a deployable device attached to it, this option may not be an acceptable approach to the Mars program. The third deployment option (fig. 5(c)) provides an option for a secondary payload on the cruise stage. The Tumbleweed vehicles would be packaged in their own aeroshells attached to the cruise stage, similar to the Deep Space 2 (DS-2) probes that flew with the Mars Polar Lander. The aeroshells containing the Tumbleweeds would be deployed from the cruise stage at the proper time following separation of the primary lander from the cruise stage. This option allows some flexibility for deployment to a different location from the primary mission; however, it is also anticipated to be more expensive than the previous two options due to the dedicated Tumbleweed aeroshells.

The last two options (fig. 6) present deployment scenarios in which Tumbleweeds are primary payloads rather than secondary “piggyback” payloads. This approach provides the advantage of deploying multiple Tumbleweed rovers in particular locations at the particular time desired; however, these concepts represent high cost missions due to dedication of the entire mission to a Tumbleweed payload. The first of the primary payload options (fig. 6(a)) presents an option similar to figure 5(a), in which the Tumbleweed is deployed from the backshell; however, in this case, there is no primary lander payload in the aeroshell, only Tumbleweed vehicles. This approach provides the option of being able to disperse a group of Tumbleweeds over a large area while the backshell is descending. The second primary payload option (fig. 6(b)) provides a concept with high heritage and proven success. The Tumbleweeds would be packaged within an airbag landing system similar to that used for Pathfinder and the Mars Exploration Rovers (MER). After successful landing and deflation of the airbags, Tumbleweed vehicles could then be deployed one at a time when the wind conditions are favorable or blowing in a particular direction.



(a) Secondary payload on entry backshell.

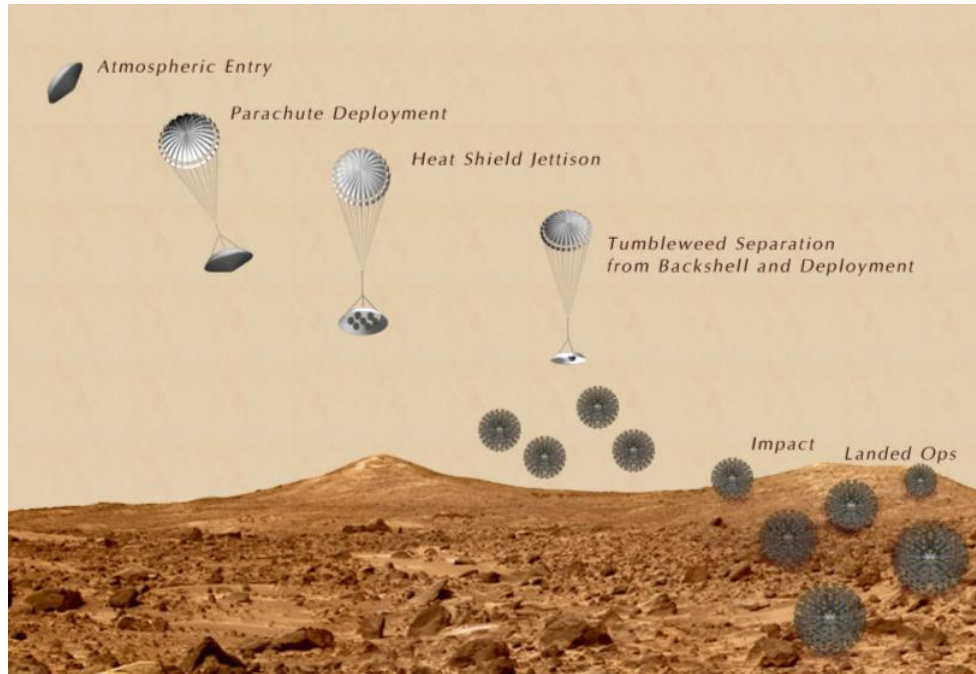


(b) Secondary payload on lander.

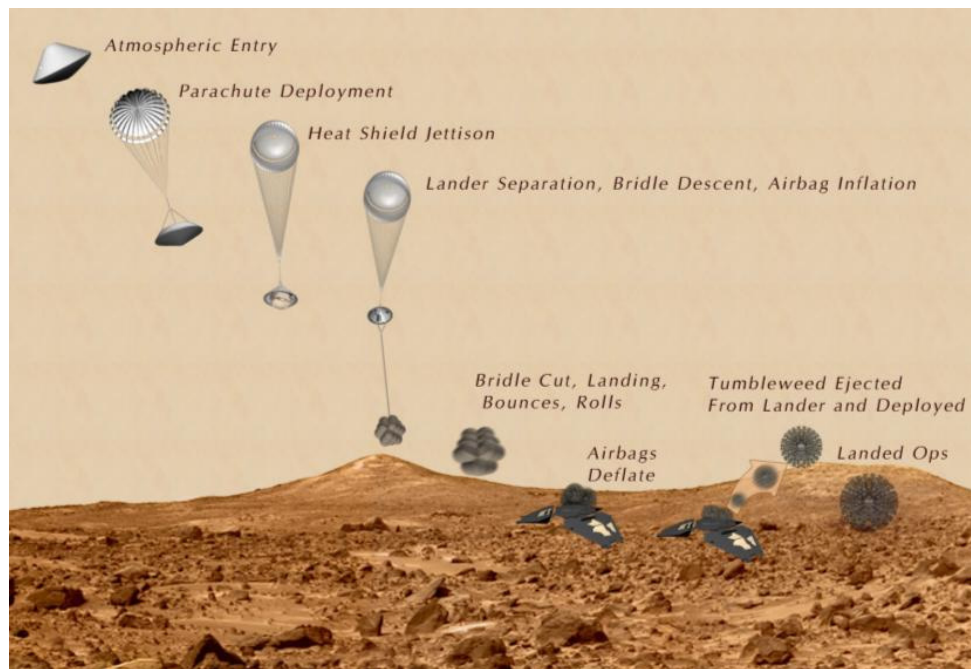


(c) Secondary payload on cruise stage.

Figure 5. Secondary payload deployment options.



(a) Primary payload—self landing.



(b) Primary payload airbag landing.

Figure 6. Primary payload deployment options.

4. Aerodynamic Testing

4.1. Overview of Testing Strategy

The overall strategy for aerodynamic testing of Tumbleweed concepts is threefold:

- Measure the aerodynamic properties of Tumbleweed concepts
 - Static testing in free-stream flow
 - Dynamic testing (rotating models) with surface effects
- Investigate boundary layer surface effects
 - Static testing in an Atmospheric Boundary Layer (ABL) wind tunnel
- Examine concepts in a relevant Martian environment
 - Testing in relevant temperatures, pressures, and atmospheric composition

The FY03 work encompassed static testing in free-stream flow and atmospheric boundary layers.

4.2. Wind Tunnel Test Results

4.2.1. North Carolina State University Subsonic Wind Tunnel

Undergraduate students from the North Carolina State University (NCSU) researched, designed, and analyzed Tumbleweed rover concepts (fig. 7) as part of a senior aerospace spacecraft design class (ref. 6). The NCSU team also designed and built a variety of Tumbleweed wind tunnel test models based on the concepts (fig. 8).

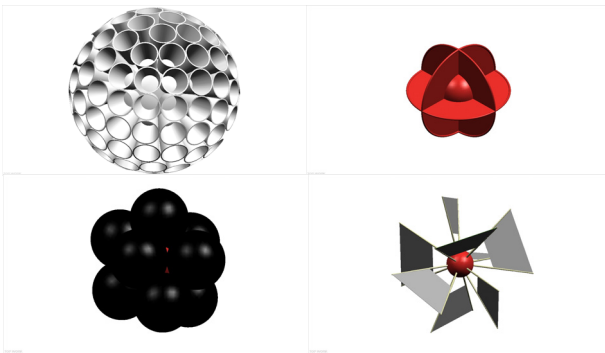


Figure 7. NCSU Mars Tumbleweed concepts.

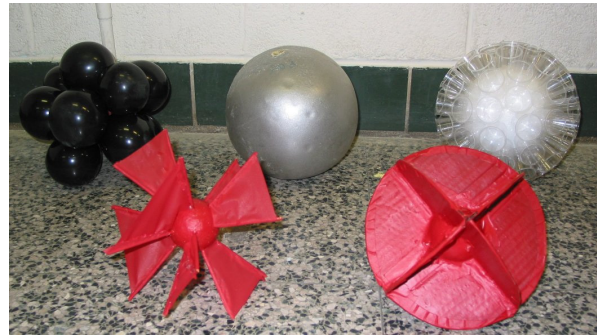


Figure 8. NCSU wind tunnel models.

The models (20 to 23 cm in diameter) were tested in the NCSU Subsonic Wind Tunnel (fig. 9) at 3.8 to 8.3 m/s wind speed, in order to match the Reynolds number to those that would be experienced on Mars ($Re = 50000$ to 150000 based on 6-m spherical Tumbleweed in Martian winds of 7 to 15 m/s). The results showed that the Box Kite had the greatest drag coefficient (C_d) (an average of ~ 1.1) over the other Tumbleweed concept models (fig. 10). However, it is important to note that angle-of-attack dependencies were not examined in the NCSU tests. The Box Kite model was oriented with one disk perpendicular to the flow, approximating the characteristics of a flat plate. Additional tests are necessary in order to understand how different orientations may change these results.

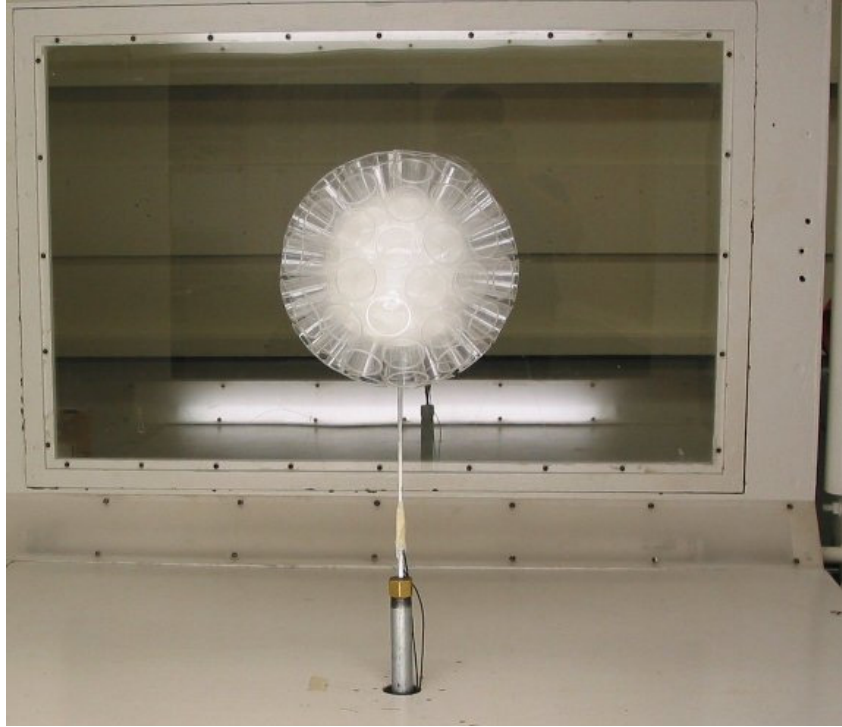


Figure 9. NCSU Tumblecup model in test section of NCSU Subsonic Wind Tunnel.

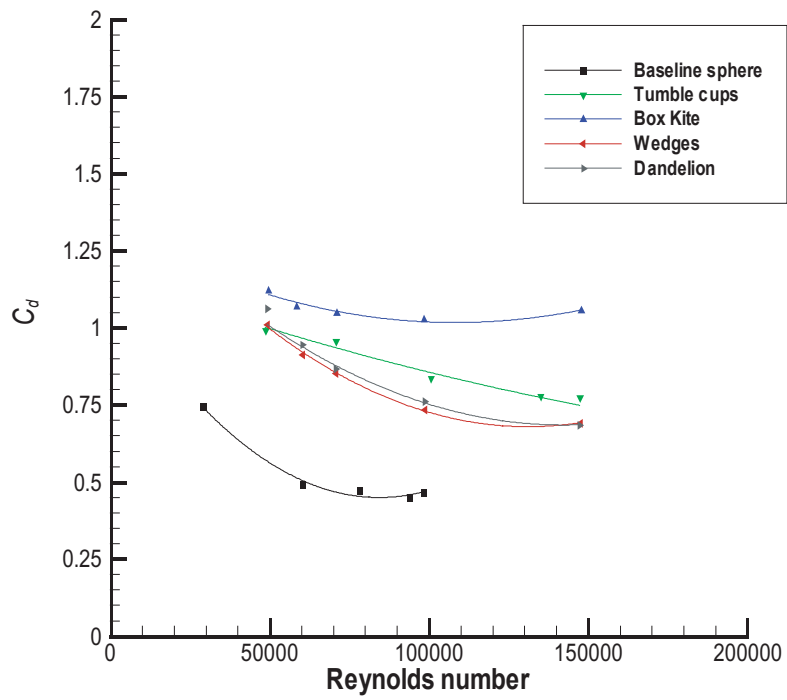


Figure 10. NCSU Subsonic Wind Tunnel results.

4.2.2. NASA LaRC Basic Aerodynamic Research Tunnel (BART)

The main objective of the LaRC Basic Aerodynamic Research Tunnel (BART) testing was to provide additional preliminary data on the aerodynamic characteristics of the various Tumbleweed rover concepts in a static free-stream flow environment for input to the dynamic simulations. An additional objective of the testing was to assist with the down-selection of Tumbleweed concepts for further development, testing, and analysis. As with the NCSU tests, the LaRC tests did not seek to duplicate a Mars relevant environment, but instead to obtain measurements at Reynolds numbers similar to those that would be experienced on Mars ($\sim 50\,000$ to $\sim 125\,000$). To accomplish these objectives, two test methodologies were used: sting-mounted force measurements and smoke visualization. The goal of the sting-mounted tests was to acquire numerical data on the basic aerodynamic properties (lift, drag, moments of inertia, and so on) of the Tumbleweed concepts. However, to complement these measurements, smoke visualization was used to discern whether any particular concept created visible disturbances to the airflow around it that could then be attributed to better drag and aerodynamic qualities.

Four Tumbleweed concepts were tested in the LaRC BART: a “Wedges” model made of Styrofoam® balls attached to a central spherical core; a “Box Kite” model using a commercially available watercraft radar reflector; and “Tumblecup” and “Dandelion” models made of stereolithography parts that could be assembled in 12, 24, or 36 cup/stem configurations. A 4-in. diameter sphere (the same core used for the Wedges, Tumblecup, and Dandelion models) was also tested to provide a baseline measurement of the well-defined aerodynamic properties of a sphere. A medium sized tumbleweed plant, roughly 14 to 20 in. in diameter, was purchased from the Kansas Prairie Tumbleweed Farm in Garden City, KS and also tested in the BART to study the aerodynamic properties from a biomimetics perspective (fig. 11).

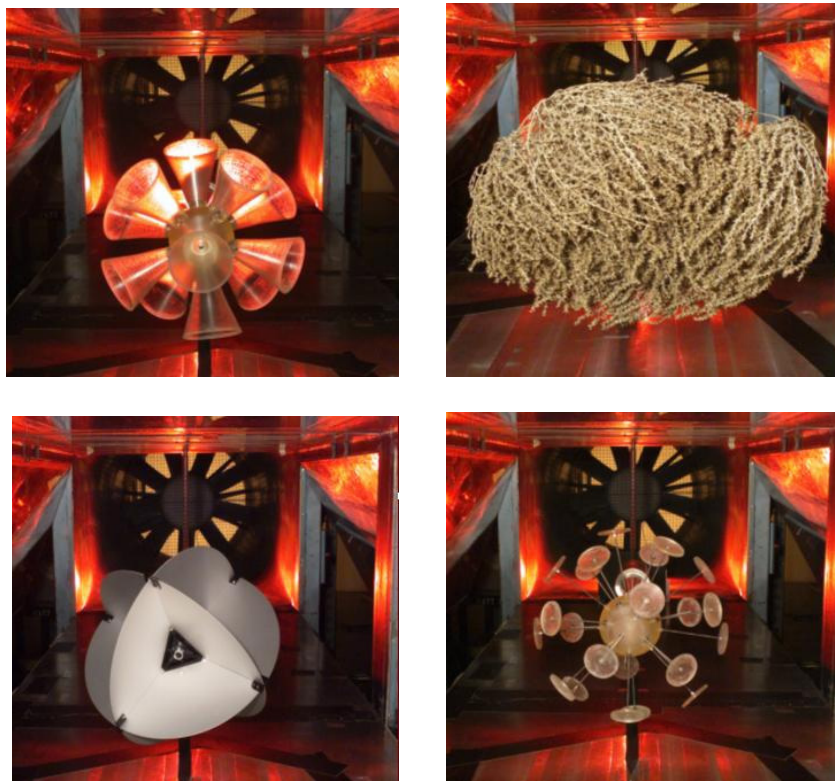


Figure 11. Tumblecup (top left), Tumbleweed (top right), Box Kite (lower left), and Dandelion (lower right) wind tunnel models in BART.

Several critical goals were defined for the stereolithography model design process. First, the models had to take the shape of the previously designed Tumbleweed concepts, specifically those of the Tumblecup and Dandelion. Second, the models had to be modular to allow for multiple configurations of both concepts as well as for disassembly for easy transport and storage. Third, the final assembled designs were each to be 12 in. in diameter so that comparative drag data could be obtained. All these goals were met. The NASA LaRC Stereolithography Lab was tasked to produce the model parts, including three central cores (one with 12 holes, one with 24, and the third with 36, outfitted with threaded inserts), the cup attachments, and the dandelion petals. The connections between these elements were accomplished through use of nuts, bolts, and threaded rod cut to appropriate lengths. Thus, the testing of three differing configurations of both Dandelion and Tumblecup models was enabled.

The Wedges design also benefited from this stereolithography work as the Styrofoam® balls were attached with the same threaded rod used for the Dandelion models to the 12-hole center core. A small watercraft radar reflector was used for the Box Kite model and included the added benefit of already including a sting adapter attachment mechanism. Finally, it was decided that because the various concepts were modeled after the Tumbleweed, the actual Tumbleweed plant should hold a distinct place in the testing as well.

The BART is an open-circuit, closed-test section tunnel located in Building 1214 at LaRC. The test section has dimensions of 28 in. high by 40 in. wide by 10 ft long and has a maximum velocity of 185 ft/s, which translates to a Re/ft of 1.14 M. Furthermore, the turbulence intensity ranges from 0.04 percent to 0.09 percent. There are a variety of flow visualization techniques available from relatively simple smoke flow (that the Tumbleweed Team used) to off-body visualization using a laser light sheet. Additional capabilities include transition detection by means of sublimating chemicals, pressure determination through the Electronic Scanning Pressure System (ESP), aerodynamic loads with one of the many internal strain gauge balances, as well as laser velocimetry and digital stereo particle image velocimetry. The BART Facility Coordinator and lead technician is Mr. Richard White and the Facility Research lead is Mr. Luther Jenkins (ref. 7).

The balance chosen for the tests was strain gauge balance 733. The BART personnel had initially suggested the HH19a because it is a lighter and more sensitive model; however, because all test models exceeded the moment arm limit of the HH19a balance, we used the 733. The characteristics of the 733 balance are displayed in appendix B. In addition, the moment center is 0.673 in. behind the centerline of the forward dowel pin. The hole in which this dowel pin is inserted can be seen in appendix B as part of the sting attachment piece that was machined for the testing. The balance excitation is 5.000 V and the delta W is 2.2706E-2 lb. This balance was last calibrated on July 9, 2002, by Engineer McWithey (ref. 8).

A test matrix was developed for both the smoke visualization and the balance tests. See table 3 for the final order and characteristics of the tests. The 12-in-diameter sphere used in the smoke tests was not used in the balance tests because its mass exceeded the force limits on the balance. Instead, the 4-in-diameter sphere was used as the baseline for the balance tests. Initially, changes in the angle-of-attack (AOA) sweep resulted from trouble with the LabView® software being used to control the arc sector. Mr. White consulted another experienced programmer and the anomaly was resolved, allowing the full range, -5° to $+30^\circ$, to be achieved.

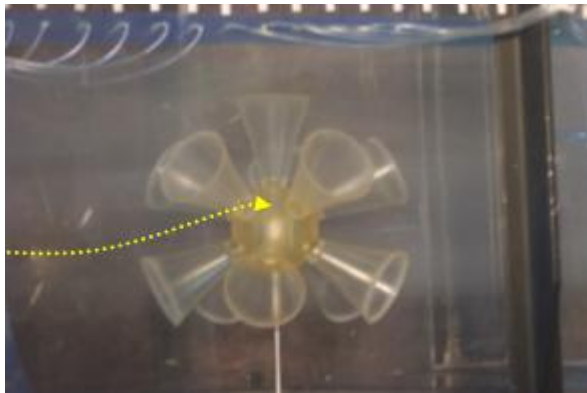
Table 3. BART Test Matrix

Run no.	Model	Test type	Velocities tested, ft/s	AOA sweep, deg
1	12-in. sphere	Smoke	11, 20, 40	
2	36 Dandelion	Smoke	11, 20, 40	
3	12 Tumblecup	Smoke	11, 20, 40	
4	24 Dandelion	Smoke	11, 20, 40	
5	12 Dandelion	Smoke	11, 20, 40	
6	36 Tumblecup	Smoke	11, 20, 40	
7	12 Dandelion inverted petals	Smoke	11, 20, 40	
8	24 Dandelion inverted petals	Smoke	11, 20, 40	
9	Box Kite on floor	Smoke	11, 20, 40	
10	Box Kite raised with plate parallel to flow	Smoke	11, 20, 40	
11	Box Kite raised with section parallel to flow	Smoke	11, 20, 40	
12	Box Kite with center hole covered	Smoke	11, 20, 40	
13	12 Dande-cup	Smoke	11, 20, 40	
14	4-in. sphere	Smoke	11, 20, 40	
15	Wedges	Smoke	11, 20, 40	
16	36 Dandelion inverted petals	Smoke	11, 20, 40	
17	Tumbleweed plant	Smoke	11, 20, 40	
18	4-in. sphere	Balance	20, 40	-5 to 10
19	36 Dandelion	Balance	20, 40	-5 to 10
20	12 Tumblecup	Balance	20, 40	-5 to 12
21	24 Tumblecup	Balance	20, 40	-5 to 12
22	12 Dandelion	Balance	20, 40	-5 to 30
23	Box Kite with center hole covered	Balance	20, 40	-5 to 30
24	36 Tumblecup	Balance	20, 40	-5 to 30
25	24 Dandelion	Balance	20, 40	-5 to 30
26	Wedges	Balance	20, 40	-5 to 30
27	24 Dande-straw-stem	Balance	20, 40	-5 to 30
28	12 Tumblecup	Balance	20, 40	-5 to 30
29	Box Kite with center hole open	Balance	20, 40	-5 to 30
30	Tumbleweed plant	Balance	20, 40	-5 to 30
31	4-in. sphere	Balance	20, 40	-5 to 30

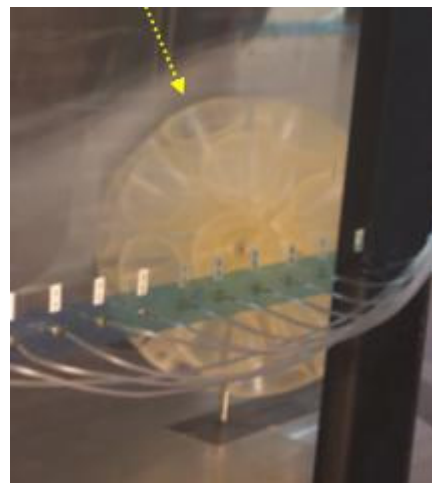
The test procedures varied for the smoke visualization and the balance tests; however, both began with integration of the appropriate model for the first run, followed by installation of the model into the test section by the BART technician. During the smoke flow visualization tests, a standard theatrical smoke/fogger machine was positioned at the front of the tunnel before the first screen. The tunnel fans were then turned on and brought up to speed, the smoke machine was activated, and finally the two video cameras focusing on the test section started recording. As the recording commenced, the time stamp displayed by the cameras was manually noted to aid post-test data reduction. After approximately 30 s had elapsed at one wind velocity, Mr. White was signaled to increase the fan speed to the next desired test point and the time stamp on the cameras was again noted. Throughout this process, still photographs were taken of the models from different angles with a digital camera, while in the control room, the next model was being configured for the next test run. After all desired velocities were achieved and videotaped, the fan was

slowed and stopped, the model was removed from the test section, the next model was installed, and the process was repeated. Time was allotted between test runs to allow for the smoke to clear from the BART facility, providing a better video and photographic environment for the next test run.

The smoke visualization tests provided a unique opportunity to view the flow over the Tumbleweed concept models. Several phenomena were observed, including flow separation off various Tumbleweed structures, which was particularly apparent with all the Dandelion models and the 12 Tumblecup model (fig. 12(a)). Boundary layers were evident across a number of the models, as a darker region would form between the outer edge of the model and the smoke flow (fig. 12(b)). The Box Kite model exhibited some particularly interesting flow dynamics, one image of which is seen in figure 13(a). Smoke was seen turning at nearly right angles as it flowed into a quadrant of the model, impacted a plate, and then turned to escape the corner and continue downstream. The Tumbleweed plant also provided an intriguing result (fig. 13(b)) as it appeared to catch most of the smoke and then allowed small, low velocity “puffs” to emerge from the backside of the plant.

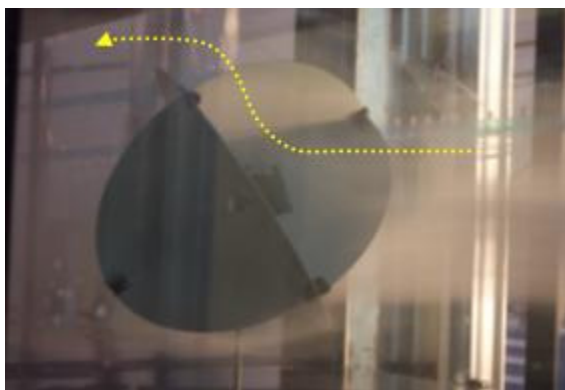


(a) 12 cup Tumblecup, 11 fps.

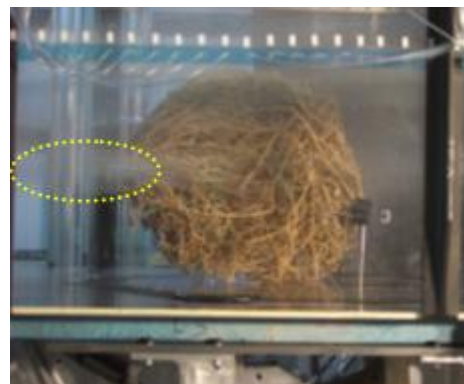


(b) 36 cup Tumblecup, 20 fps.

Figure 12. Tumblecup smoke flow visualization.



(a) Box Kite, 20 fps.



(b) Tumbleweed plant, 11 fps.

Figure 13. Box Kite and Tumbleweed plant smoke flow visualization.

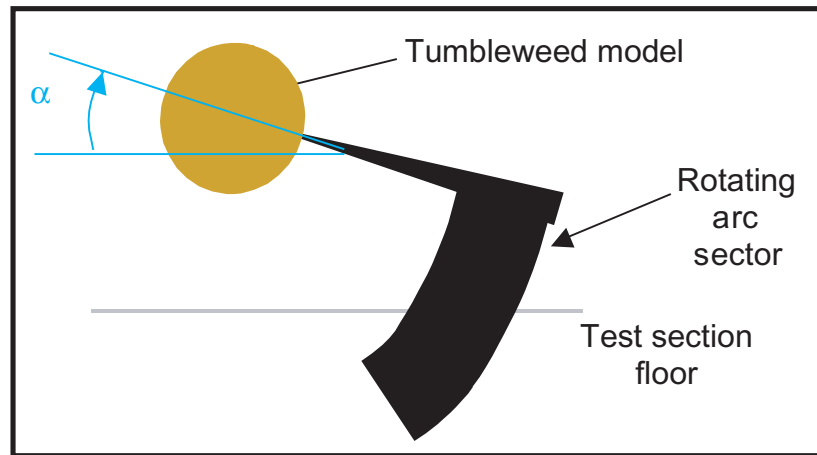


Figure 14. Test configuration for force measurements.

After all smoke visualization test runs were completed, the team stood-down for approximately one-half day to allow for installation of the arc sector, which provides the capability for the sting-mounted models to be swept through a range of AOA. A diagram of the arc sector-balance-sting setup within the test section is seen in figure 14. The symbol alpha (α) denotes the model AOA.

Once the appropriate model was installed in the tunnel, a “tare” (zeroing of the balance) was conducted by sweeping the arc through all AOA tests without the fan operating to create loads, and by taking a reading to establish the starting or zero point. The model was then returned to 0° AOA and the tunnel’s fan was brought up to speed. As soon as the flow appeared stable at the appropriate velocity, the arc sector began the sweep of AOA starting at -5° and ending at 30° , in 1° increments from -5° to 10° , and in 2° increments from 10° to 30° . After a full AOA sweep was conducted, a second and third sweep was conducted to gather three full sets of data that could be averaged. When the third sweep at the first velocity was complete, the fan speed was increased to the second velocity and the procedure of three AOA sweeps was repeated. When all six sets of data for a single model were gathered, the fan was decelerated and stopped, the model in the test section was removed, and the next model was installed.

The sting-mounted tests led to several definitive results. The values of C_d , as well as the smoothness of the data collected, varied with wind speed (and thus Reynolds number). The flow through BART was very unsettled at 20 ft/s, but smoothed considerably at 40 ft/s. The majority of the Tumbleweed concepts tested have drag characteristics that are independent of the AOA, based on the plots of drag coefficient (C_d) versus AOA, as seen in figures 15 and 16. The main exception to this finding is the Box Kite, which is greatly AOA dependent as illustrated by the highly sloped line in both figures. However, the C_d for Box Kite is higher than those of the other concepts for over a significant portion of the tested AOA and has a C_d in the range of the other concepts throughout the rest of the AOA. A rank ordering of the concepts was completed using the measured C_d values with the Box Kite being first, followed closely by the 24 and 36 Tumblecups, then the 12 Tumblecup, along with the Dandelion concepts and the Wedges concept falling last, just slightly above the 4-in. sphere. Also interesting to note from figures 15 and 16 is that most of the Tumbleweed concepts have C_d values very close to each other. Additionally, the ranking of a particular concept remained basically unchanged, regardless of the wind speed; however, only a limited number of wind speeds were run (20 ft/s and 40 ft/s). The drag coefficients (C_d) were calculated by using the projected area of the models, which is not necessarily the most appropriate method; follow-on data reduction efforts in FY04 will examine several alternative methods of calculating the C_d .

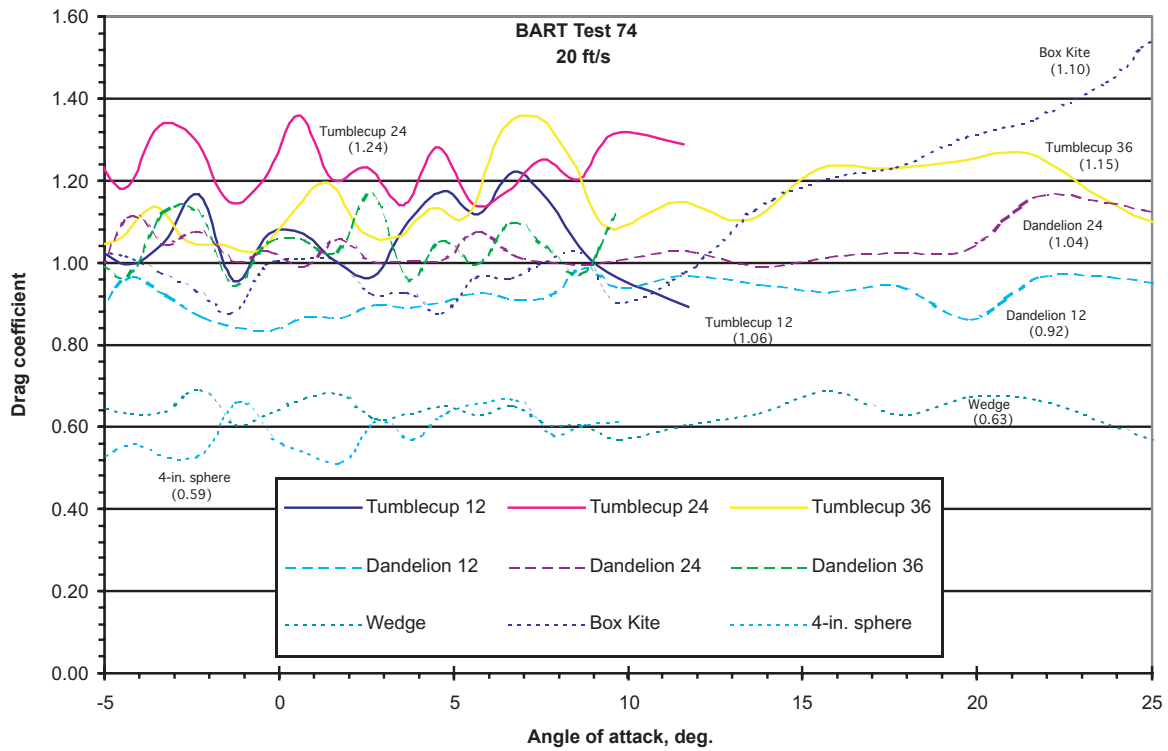


Figure 15. Tumbleweed test results at 20 fps ($Re = 128\,000$).

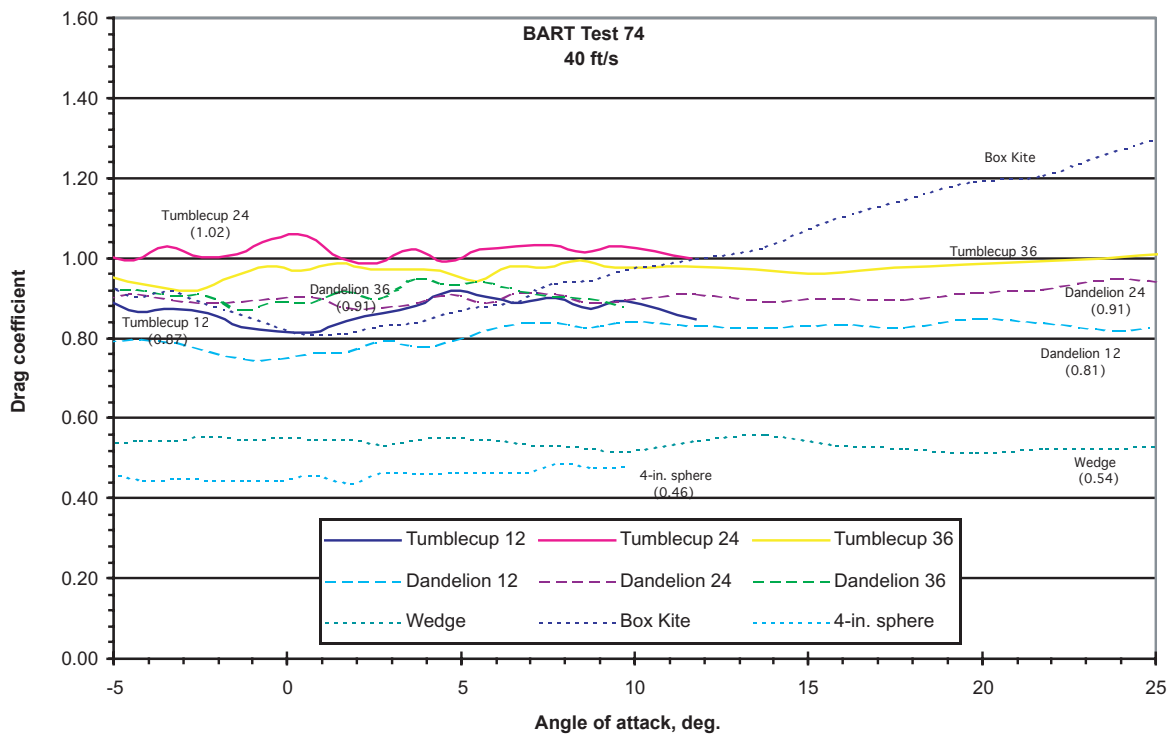


Figure 16. Tumbleweed test results at 40 fps ($Re = 256\,000$).



(a) 24 stem Dandelion at 0° AOA.



(b) Wedges at positive AOA.

Figure 17. Sting-based tests.

Figure 17 shows the test setup for the sting-based tests, with a 0° AOA case (fig. 17(a)) and a positive AOA pitch (fig. 17(b)).

Therefore, based on the data obtained, reduced, and analyzed from the Tumbleweed wind tunnel testing conducted in the BART, several conclusions and recommendations for future testing opportunities can be made. First, the baseline 4-in. sphere should be a part of each test conducted in the future, regardless of the venue, to allow for baseline comparisons between datasets. Second, the “Wedges” concept, as it was tested, needs to be dismissed from consideration for the final Tumbleweed design due to poor aerodynamic performance. Third, the top three models for continued testing are the Box Kite, the 24 Tumblecup, and the 24 Dandelion (with inverted pads). As discussed above, each of these models exhibited unique and intriguing phenomenon and appear to be the best aerodynamically suited concepts. These three models, configured just as they were for the FY03 BART tests, should be the subjects of future tests: (1) to determine behavior in the desired Reynolds number environment ($\sim 25\,000$ to $\sim 125\,000$); (2) in a simulated Mars atmospheric boundary layer (ABL); and (3) in a Mars relevant environment that simulates the density, pressure, and temperature on Mars. Further tests of these models in a facility such as the BART would be best suited to configuration refinement with some suggested areas of study shown below. However, the following list of testing options is neither exhaustive of all possibilities nor firmly set:

- Box Kite model
 - Open and closed center hole
 - Recessed sails
 - Additional structural rings
- Tumblecup 24 model
 - Varying cup sizes
 - Varying cup/cone angles (wider cups versus narrower cups)
- Dandelion 24 inverted model
 - Smaller radius of curvature on inverted petals
 - Larger diameter petals
 - 36 stems (rather than 24)

Fourth, the remaining models that were investigated in the FY03 BART testing (the 24 Dandelion Straw Stem, the 12 Tumblecup, the 36 Dandelion, and the 24 Dandelion) should not be completely eliminated from consideration for the final Tumbleweed design as the specific science or instrumentation goals of the mission may require or best be suited to one of these designs.

Several concerns were raised during and after the wind tunnel testing concluded. First, the wake rake placed in the test section downstream of the model may have been too far behind the trailing edge of the model to accurately record the differences in the flow characteristics between the different Tumbleweed concepts. Despite reassurances that the overall turbulence, size, and speed are not affected by the downstream distance, it would be interesting to compare these data with those resulting from the rake being placed within 0.33 m of the rear of the models to determine whether individual flow characteristics of each model type could be observed. Second, there was a concern regarding the steadiness of the flow through the BART test section at lower speeds. Testing at the desired Mars relevant Reynolds numbers (~25000 to 125000) could not be performed in the BART using the current models and the 733 balance. Additional tests are planned in the BART for FY04 which may be able to achieve the desired Reynolds numbers by using smaller, lightweight models and a more sensitive balance.

4.2.3. Texas Technical University Boundary Layer Wind Tunnel

Dr. Alan Barhorst and Dr. Darryl James of the Texas Technical University (TTU) are preparing to test Tumbleweed concepts in a simulated Mars ABL based on data from the Mars-GRAM 2001 atmospheric model (fig. 18). The testing will determine the drag coefficient of various Tumbleweed concepts in the ABL for comparison with drag coefficients obtained from a uniform flow. Uniform flow tests are currently being conducted on TTU Tumbleweed concepts (fig. 19), with the ABL tests planned for completion in the spring/summer semesters of 2004.

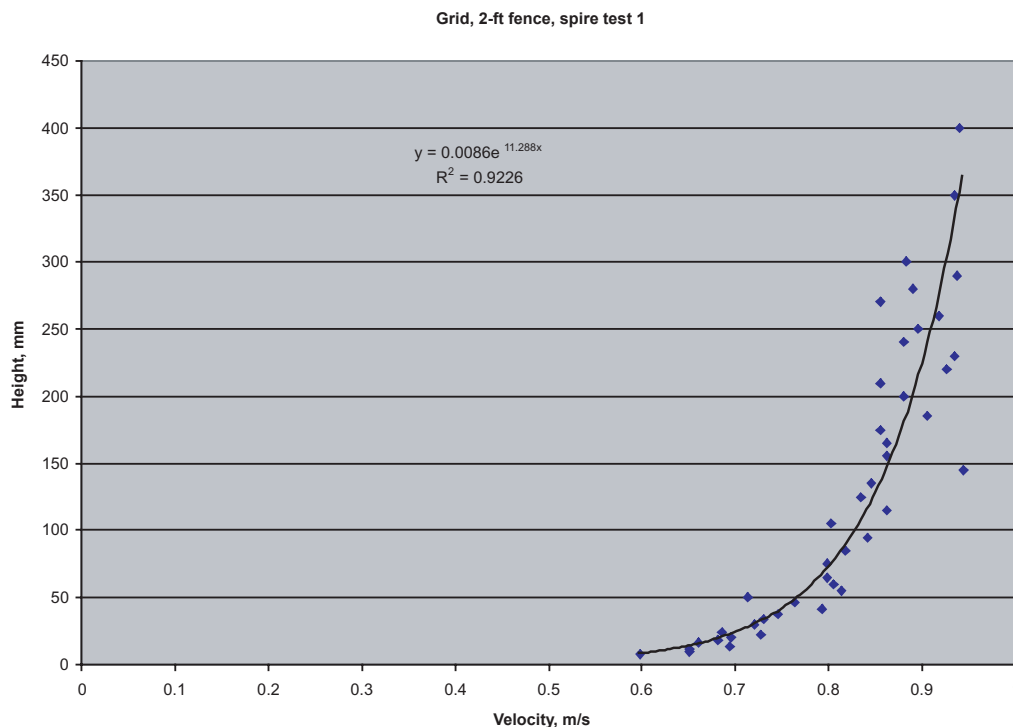
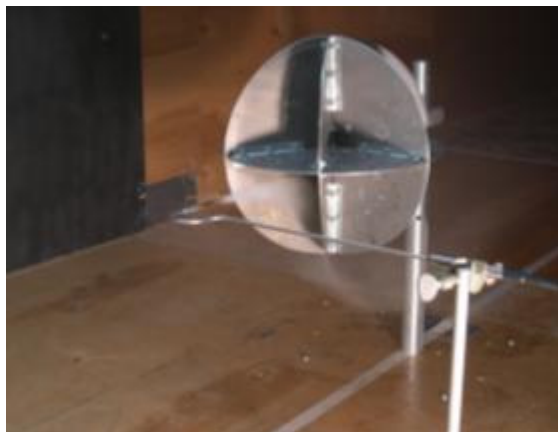


Figure 18. Predicted parabolic boundary layer profile scaled to earth test conditions.



(a) TTU Tumbleweed uniform flow test setup.



(b) Smoke flow visualization.

Figure 19. TTU Tumbleweed wind tunnel tests.

4.3. Summary

The aerodynamic testing opportunities for FY03 provided valuable data to the LaRC Tumbleweed team. The NCSU tests provided data for similar Tumbleweed designs to those tested by the LaRC team, at lower Reynolds numbers. Additionally, while the testing planned by Texas Tech University in the ABL tunnel was delayed, the analytical work matching the Mars boundary layer profile was completed in preparation for testing in FY04. The LaRC BART tests provided the team with a greatly enhanced understanding of the basic aerodynamic characteristics of the main Tumbleweed concepts under consideration as well as considerable experience in designing and running a test. As a result of this work, the direction of future testing is being defined and an additional entry into the BART has been secured for summer FY04.

5. Dynamic Analysis and Testing

5.1. Summary of Analysis Plan

Approach: Develop simplified math models to continue investigation of key dynamic characteristics of the Tumbleweed rover. Dynamics simulation development will be split into two separate efforts. One effort will focus on the development and validation of the basic physics-based models of rolling, sliding, and bouncing dynamics of a generic flexible Tumbleweed structure. The other effort will focus on development of simulation tool architectures for providing end-to-end Monte Carlo dynamics simulations using representative Martian terrain. These two efforts will serve as a basis for future development of Tumbleweed 6 DOF Monte Carlo simulator used to model motion over simulated Mars terrain.

5.2. Continuation of Feasibility Studies

Additional feasibility studies were performed that built on the results of the initial feasibility studies performed in FY 2002 (ref. 1). The studies performed continued to explore the necessary Tumbleweed rover properties for impending motion in a variety of worst-case situations. In FY 2003 there were two situations that these additional studies focused on: static analysis of a Tumbleweed rover trapped on a rocky slope and a simplified dynamics analysis of a Tumbleweed rover impacting a rock. These feasibility studies have helped build a fundamental understanding of the problem and guide future analysis

efforts. Additionally, they indicate, from a basic physics standpoint, that the Tumbleweed rover concept is feasible and thus continues to be a worthwhile research venture.

5.2.1. Static Analysis of Tumbleweed Rover Trapped on Rocky Slope

On the Martian surface, wind speeds and directions vary constantly. Wind speeds vary from 2 to >25 m/s depending on the season, time of day, and weather conditions. Winds typically cease all together at night. Consider a Tumbleweed rover traveling along and being pushed by a 7-m/s afternoon breeze. The Sun will eventually set, the winds will die down, and the rover will probably stop moving until the winds pick up again the next day. As a worst-case scenario, the Tumbleweed could possibly stop on a slope and become lodged between several rocks. What wind speed will then be required to nudge that Tumbleweed out of its resting place? Is a wind of this speed one the Tumbleweed is likely to encounter? What slopes and rock sizes can a particular Tumbleweed rover overcome? Will the Tumbleweed rover be able to continue its mission up the slope after becoming trapped as described previously? This feasibility study attempts to answer these questions.

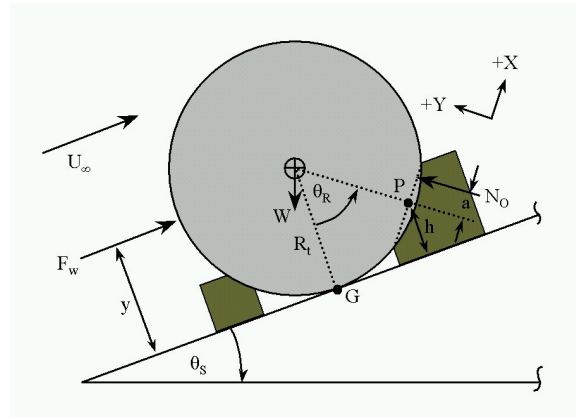


Figure 20. Free body diagram of Tumbleweed rover trapped on sloped surface.

Figure 20 shows a free body diagram of a Tumbleweed rover trapped on a slope of angle θ_s . The Tumbleweed rover is assumed to be a nonrigid sphere. At rest with zero wind, the Tumbleweed's weight would act entirely through point G on the slope face. As the wind force (F_w) exerted on the Tumbleweed increases, the weight that was exclusively distributed through point G at rest begins to shift over to point P on the rock face. This motion continues through increasing wind velocities (U_∞) until finally the Tumbleweed's entire weight is distributed through point P . At this point in the transition, any increase in U_∞ will enable the Tumbleweed to overcome the rock and continue upslope. Therefore, when summing moments about point P , the following equation defines when F_w is sufficient to push the rover past the upslope rock:

$$M_{F_w} > M_W + M_{N_o} \quad (1)$$

M_{F_w} is the moment about point P exerted on the Tumbleweed as a result of the wind force F_w and is defined by

$$M_{F_w} = [C_D A_{\text{ref}} q \sin(90 - \theta_R)](R_t - c) \quad (2)$$

where C_D is the drag coefficient of a given Tumbleweed vehicle, A_{ref} is the cross-sectional area, θ_R is the rock angle, R_t is the radius of the Tumbleweed, c is the deformation distance of the rover's structure under loading (given by $2\mu_r^2 R_t$ where μ_r is the coefficient of rolling resistance defined by the ratio a/R_t (ref. 1)), and q is the dynamic pressure, given by

$$q = \frac{1}{2} \rho U_\infty^2 \quad (3)$$

with ρ being the atmospheric density and U_∞ the free-stream velocity.

M_W is the moment about point P pulling the Tumbleweed downslope and is defined by

$$M_W = W_X (R_t - c) \quad (4)$$

where W_X is the Tumbleweed weight component in the X direction given by $W \sin(\theta_R + \theta_S)$ with θ_R as the rock angle and θ_S as the slope angle. For typical aircraft tires, ranges for μ_r can be anywhere from 0.02 to 0.3, depending on the flexibility of the tire and the rolling surface conditions (ref. 9). The range considered in this study was 0 to 0.15.

For this analysis, it is assumed that the wind force acts through the Tumbleweed's center of gravity. In reality, the center of pressure would be offset somewhat due to boundary layer effects. However, presently the significance of these boundary layer effects is unclear and is something that future analyses will need to address. An effort is being made to characterize the Martian boundary layer, and is discussed in section 4.2.3.

M_{N_O} is the moment about point P caused by the flexible Tumbleweed's resistance to rolling and can be accounted for by assuming an offset normal force.

$$M_{N_O} = N_O a \quad (5)$$

N_O is the offset normal force, which is contributed to by the Y direction components of the Tumbleweed weight and wind force. It then follows that this offset normal force is given by

$$N_O = [W \cos(\theta_R + \theta_S)] + [C_D A_{\text{ref}} q \cos(\theta_R + \theta_S)] \quad (6)$$

The distance a is the amount of normal force offset from the contact point P and is given by $\mu_r R_t$.

Figures 21 and 22 show wind speed versus rock height for a particular Tumbleweed rover configuration on flat ground and on a 30° slope, respectively. The Tumbleweed's radius was varied from 1 to 4 m, while the mass, drag coefficient, and coefficient of rolling resistance were all held constant. However, any of the Tumbleweed design parameters described previously can be varied within the analysis codes developed for this study. The drag coefficient of 1.0 was selected based on values obtained from the wind tunnel testing discussed in section 4.

From figure 21, consider a 3-m radius Tumbleweed. On flat ground, a 16-m/s wind will be required to overcome a 1.0-m high rock. As expected, for a 4-m radius Tumbleweed, a slower wind, roughly 10 m/s, will be needed to overcome the same 1.0-m rock. We also see that the 1- and 2-m radius Tumbleweeds are at best only capable of overcoming relatively small rocks at very high wind speeds.

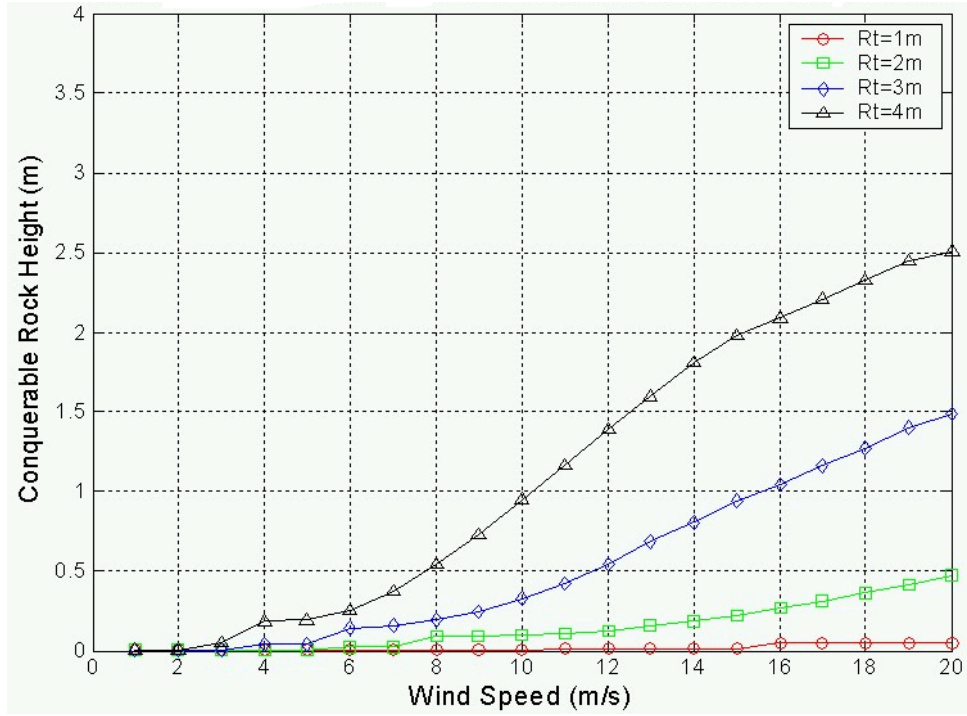


Figure 21. Wind speed versus rock height for Tumbleweed on flat ground; $C_d = 1$, $M_t = 110\text{kg}$, $C_r = 0.15$.

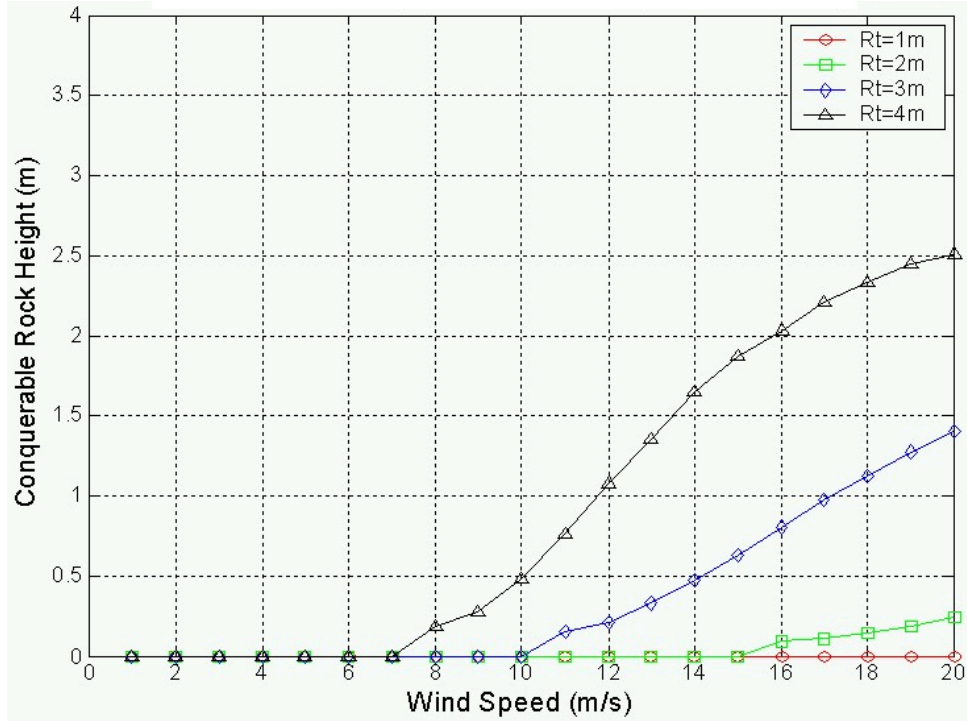


Figure 22. Wind speed versus rock height for Tumbleweed on sloped surface; $\theta_S = 30^\circ$, $C_d = 1$, $M_t = 10\text{kg}$, $C_r = 0.15$.

Now consider the same 3- and 4-m Tumbleweeds from figure 22, where there is now a 30° slope to overcome as well. For lower wind speeds, the 3- and 4-m Tumbleweeds now require a 17-m/s and 12-m/s second wind, respectively, to overcome that same 1.0-m high rock. However, by comparing these two charts, one notices that the wind speed requirements for conquering a rock on flat ground and conquering a rock on a sloped surface become similar as the velocity increases. In other words, the 4-m Tumbleweed, regardless of whether it is on a flat or sloped surface, requires a 20-m/s wind to overcome a 2.5-m high rock. The same trend is apparent for the 3-m Tumbleweed and also when other design parameters such as mass and drag coefficient are varied. This result implies that, for slopes $\leq 30^\circ$, as the wind speed approaches 20 m/s the moment created by the wind force becomes dominant, eventually negating the effects of gravity pulling the Tumbleweed back down the slope. For slopes $> 30^\circ$ this effect would eventually surface as well, but at higher wind speeds.

In conclusion, this study shows that Tumbleweed rovers of reasonable size and mass can overcome substantial rock impedances on relatively extreme slopes. A 30° slope on Mars is not common over long distances and is a very conservative estimate of a worst-case condition. Similarly, the large rocks considered in this study (1.0 to 2.5 m) are not common features on the Martian surface and would also be very conservative, worst-case condition assumptions. The wind speeds required to dislodge a Tumbleweed rover in this situation (approximately 10 to 20 m/s, depending on the slope angle, rock size, and Tumbleweed configuration) are not common. However, they are not unheard of. Wind speeds average from 2 to 5 m/s during the day with relatively strong gusts of 10 to 20 m/s. Seasonal dust storms can produce winds exceeding 25 m/s; therefore, a lodged Tumbleweed rover may have to wait for a sufficiently strong wind to push it out of its entrapment, but across most areas of Mars it will be hard pressed to render itself permanently immobile.

5.2.2. Simplified Dynamic Analysis of a Tumbleweed Rover Impacting a Rock

An additional feasibility study was undertaken to examine, on a fundamental preliminary level, the dynamics of a Tumbleweed rover impacting a rock. Consider a Tumbleweed rover rolling on a flat surface at a given velocity exposed to a constant wind. Somewhere along the way, the Tumbleweed hits a rock and bounces up into the free stream. What is the significance of wind pushing the Tumbleweed downrange compared to the same scenario in a zero wind environment? What pre-impact velocity is required to enable the rover to bounce up and over the rock and not back and in the opposite direction from which it came? This feasibility study attempts to answer these questions.

Figure 23 shows the free body diagram of a Tumbleweed rover impacting a rock. The Tumbleweed and the rock are assumed to be rigid structures. Collisions between the Tumbleweed and the rock and the Tumbleweed and the ground were modeled as “billiard ball” collisions with assumed coefficients of restitution. Before impact with the rock, the Tumbleweed has some initial velocity V_i . After impact with the rock, the Tumbleweed will have some velocity V_f in the direction θ_T from the horizontal. The rock is fixed to the ground and does not acquire any velocity after the collision. The initial velocity vector can be broken up into components that are parallel (t direction) and normal (n direction) to the point of impact P . It then follows that the post and pre-impact velocities are related as follows:

$$V_{f_t} = V_{i_t} \quad (7)$$

$$V_{f_n} = -eV_{i_n} \quad (8)$$

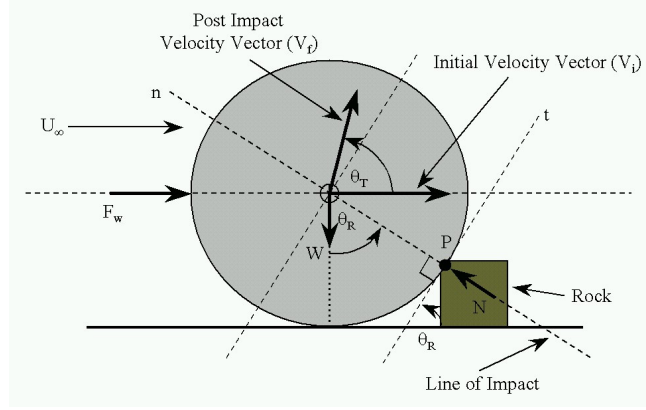


Figure 23. Free body diagram of Tumbleweed rover impacting rock.

V_{f_t} and V_{i_t} are the post- and pre-impact velocities of the Tumbleweed in the tangential (t) direction, respectively. V_{f_n} and V_{i_n} are the post- and pre-impact velocities of the Tumbleweed in the normal (n) direction. The coefficient of restitution is defined by e and is arbitrarily assumed to be 0.7 for both rock and ground Tumbleweed impacts. It is necessary to note that assumptions regarding structural properties of the Tumbleweed, such as flexibility and coefficient of restitution, are arbitrary at this point in the project. Further development of the rover's structural design parameters, such as mass, size, and construction materials, will be required to move to higher fidelity dynamics analyses.

The final, post-impact velocity of the Tumbleweed is then given by

$$V_f = \sqrt{V_{f_t}^2 + V_{f_n}^2} \quad (9)$$

and the post-impact trajectory angle θ_T is given by

$$\theta_T = \theta_R + \tan^{-1} \left(\frac{V_{f_n}}{V_{f_t}} \right) \quad (10)$$

where θ_R is the rock angle defining the size of the rock. From this final velocity and trajectory angle, it is then possible to compute the Tumbleweed's post-impact, normal projectile trajectory. Going one step further, the contribution of the free-stream wind to the Tumbleweed's downrange motion can also be approximated by accounting for the relative wind velocity acting on the Tumbleweed.

Figure 24 shows the trajectory of a particular Tumbleweed configuration impacting a rock defined by a 30° rock angle (θ_R), which translates to a rock approximately 0.4 m high. The red plot shows the post-impact trajectory of the Tumbleweed if there were no wind contributing to downrange motion, the motion of a normal projectile. The green plot shows the post-impact trajectory of the Tumbleweed accounting for the downrange contribution of the free-stream wind push. In a 6-m/s wind, the wind contribution is significant, doubling the achieved downrange motion in the same number of bounces.

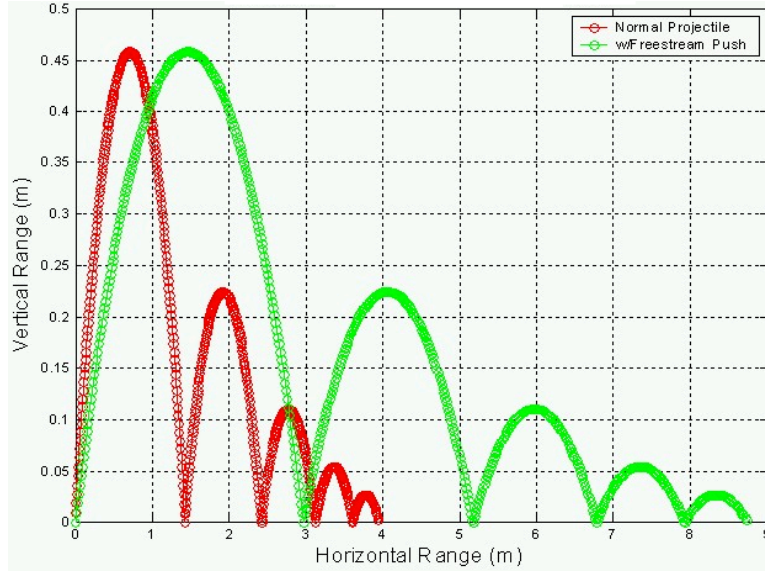


Figure 24. Tumbleweed trajectory after rigid body collision with a rock. $R_T = 3\text{m}$, $m = 10\text{kg}$, $C_d = 0.5$, $e = 0.7$, $\theta_R = 30^\circ$, $V_i = 2.5\text{ m/s}$, $U = 6\text{ m/s}$.

Figure 24 also shows that the initial velocity of the Tumbleweed was sufficient enough to allow the Tumbleweed to bounce high enough, approximately 0.45 m, to clear the top of the 0.4-m rock. Additionally, it can be seen that the trajectory angle, θ_T , is less than 90° , which maintains the forward momentum of the Tumbleweed, enabling it to progress over the rock instead of bouncing off in the opposite direction from which it originally came. From this simple analysis, rough approximations can be made for initial Tumbleweed velocity requirements necessary to dynamically conquer rocks of various sizes.

5.3. Commercial off the Shelf (COTS) Analysis Tool Study

In addition to the ongoing development of the 2-D simulation test bed, several COTS software packages were studied to evaluate their dynamics analysis capabilities and potential application to the Tumbleweed dynamics problem. More specifically, the main objective of the study was to evaluate the fidelity of each COTS package when it was used for modeling sphere-to-surface interactions to simulate a Mars Tumbleweed rover. If a capable COTS software package were found, it would be a valuable contribution to the ongoing development of the in-house, 2-Dimensional Simulation Test Bed, as well as to the dynamics analysis activity as a whole, by serving as an additional independent modeling tool. The three software packages that became the focus of the study were Maya® (Alias/Wavefront), ADAMS® (MSC Software), and Vortex® (CM-Labs).

Due to the nonlinearities and complexities of the full-scale simulation of a Tumbleweed rover in motion, it is difficult to determine the accuracy of any analysis output directly. Instead, several test cases that have well-known and easy-to-determine analytical solutions were designed (e.g., translation, rotation, friction, gravity, and so on). These test cases were then assembled within each software package, and their output results were compared to the known analytical solutions. While passing each of these tests does not ensure fidelity in the full-scale simulation, failing one or more of the tests clearly indicates weaknesses in the tool's analysis abilities. A basic description of these test cases follows, along with the associated requirement for each.

Translation

The translational motion of an object must obey

$$F = ma \quad (11)$$

where F is the force acting on the Tumbleweed, m is mass, and a is acceleration.

Rotation

The rotation motion of an object must obey

$$T = I\alpha \quad (12)$$

where T is torque acting on the Tumbleweed, I is the mass moment of inertia, and α is the angular acceleration.

Friction

It must be possible to model static and dynamic friction. Static friction must allow specification of a constant force that must be overcome before sliding motion starts. Dynamic friction must obey

$$F_F = \mu N \quad (13)$$

where F_F is the friction force, μ is the coefficient of friction, and N is the normal force. For a rolling body it must be possible to specify an initial rolling resistance, which must be overcome before the body will move, and a dynamic rolling resistance separate from the dynamic friction that opposes the sliding of the rolling body.

It is necessary to note here that dynamic friction is not the same as rolling resistance. Dynamic friction is the result of one surface moving over another and does not occur for a body rolling without slipping. Rolling resistance arises due to other effects, mainly flexibility of the rolling object, which leads to deformations and energy dissipation. Static friction does not prevent a rolling body from moving; it causes it to roll without slipping.

Gravity

It must be possible to model the effects of gravity and to be able to specify the field strength to that of Mars.

Wind

It must be possible to model a constant wind force and to be able to introduce random gusts. The wind force of an object must obey

$$F = C_D A_{\text{ref}} q \quad (14)$$

Recalling equation (3) from section 5.2.1, it is important to note that for a moving Tumbleweed, the free-stream velocity equates to the relative velocity between the wind and the Tumbleweed.

Collisions

It must be possible to model the collision of a moving object with a static object of arbitrary shape. It must also be possible to specify the coefficient of restitution between two surfaces.

Terrain

It must be possible to import a representation of terrain via a terrain database and model collisions of a moving object with the imported terrain.

Summary of Activity and Results

Table 4 summarizes the results of the COTS analysis tool study discussed in this section. Each entry labeled “Pass” indicates that the test results agreed with the known analytical solutions and that little or no special measures were needed to make the software work properly. Entries labeled “Fail” indicate that the software was incapable of reproducing the known analytical solutions or that it was impractical to model the problem correctly within the tool for that particular test case. Entries labeled “Marginal” indicate that the software only worked on some levels for a particular test case.

Table 4. COTS Tool Analysis Results

	Translation	Rotation	Friction	Gravity	Wind	Collisions	Terrain	Slide-to-roll
MAYA®	Pass	Fail	Pass	Pass	Fail	Marginal	Pass	N/A
ADAMS®	Pass	Pass	Pass	Pass	Pass	Fail	Marginal	Pass
Vortex®	Pass	Pass	Marginal	Pass	Pass	Pass	Pass	Pass

MAYA® Shortcomings

- **Rotation test: Fail**
Moments of inertia cannot be specified. Furthermore, the default values for an object’s moments of inertia are very inaccurate. For a uniform density sphere and a thin walled hollow sphere, the MAYA default moments of inertia are off by factors of 3.36 and 2.0, respectively.
- **Wind test: Fail**
The net force acting on the object is treated as being linearly proportional to the relative velocity of the object. This statement is incorrect. The net force of the wind acting on an object should be proportional to the square of the relative velocity.
- **Collisions test: Marginal**
Coefficient of restitution not properly defined.

ADAMS® Shortcomings

- **Collisions test: Fail**
Proper trajectory of a bouncing ball with a specified coefficient of restitution could not be reproduced.
- **Terrain test: Marginal**
Without the ADAMS®/Exchange module, the ADAMS®/Solver will only except computer-aided design (CAD) files of a Parasolid format (from Unigraphics). In addition, ADAMS® exhibited some instabilities regarding certain Parasolid files.

Vortex® Shortcomings

- **Friction test: Marginal**
Vortex only uses a single coefficient of friction and does not model static friction separately from dynamic friction.

As a result of this study, for testing purposes, the Vortex® software package was identified as a good choice for analysis of the Tumbleweed rover dynamics problem. A developmental analysis tool was

developed around the Vortex® software and is discussed in section 5.4.1. However, it should be noted that since the development of the Vortex® application, several prior issues with the ADAMS® software have been resolved. For various reasons the ADAMS® software could provide a high fidelity analysis capability. See *Mars Tumbleweed Rover COTS Analysis Report* (ref. 10) for further details regarding the COTS analysis tool study.

5.3.1. Evaluation of Mars Tumbleweed Rover Monte Carlo Simulator

Using Visual C++ 6.0, a wrapper application called the Mars Tumbleweed Monte Carlo Simulator, or just Tumbleweed simulator for short, was created to drive the Vortex simulation software. The current developmental version of the Tumbleweed simulator allows the user to perform preliminary Monte Carlo simulations for the purpose of evaluating the statistical distributions of Tumbleweed rovers over a Mars relevant terrain. In other words, a virtual environment can be created within the tool to examine the performance of various Tumbleweed rover configurations.

A comprehensive evaluation of the developmental Tumbleweed simulator was performed to determine the current analysis capabilities of the tool and to identify areas for future improvement. Several different Tumbleweed rover configurations and a Mars relevant terrain were modeled within the Tumbleweed simulator. The evaluation was structured to answer three basic questions. Each question is addressed below and is accompanied by the relevant identified improvement areas. Improvement of the tool is a goal of the FY2004 activities.

Question 1. Can a realistic Mars environment be modeled within the simulator?

The Tumbleweed simulator allows the user to define terrain size, rectangular rock dimensions for an upper bound large rock and a lower bound small rock, the number of rocks at each boundary that will be included on the terrain, and a number of rectangular rocks sized randomly in between the specified upper and lower bounds. The current version of the simulator includes one other terrain option that allows the user to enter in a specified terrain profile, which in general would consist of a 2-D array of vertical heights. This option could be used to create riverbeds, craters, or other sloping surfaces. However, simulating a relevant Mars rock field is the most difficult terrain-modeling challenge, as well as the toughest to analyze. Therefore, for this evaluation, the capability of the simulator to model a rocky Martian plain was the focus.

At the time of this analysis, detailed, high-resolution terrain data for Mars were limited to the landing locations of the Viking and Pathfinder missions. For this evaluation, the Viking 1 landing site was arbitrarily chosen. Figure 25 shows the cumulative number of rocks per square meter as a function of rock diameter (ref. 11). The curves on this figure were plotted from mathematical expressions derived from stereo measurements at the Viking 1 landing site.

As discussed previously, the current version of the Tumbleweed simulator only provides the user with control over the number and dimensions of the upper and lower bound rocks. If the user then wishes to place rocks of different dimensions onto the terrain, their only option is to specify a number of rocks to be randomly sized somewhere in between the dimensions of the already specified upper and lower bound rocks. Working within this restriction, a number of large rocks (2-m cubes) and small rocks (1-m cubes) were chosen for the terrain. These sizes were chosen to create a rock field that would be difficult for the Tumbleweed rover to navigate. The idea was that the difficult terrain would challenge the capabilities of the Tumbleweed simulator while at the same time offer an interesting environment to observe the dynamics of the Tumbleweed rover.

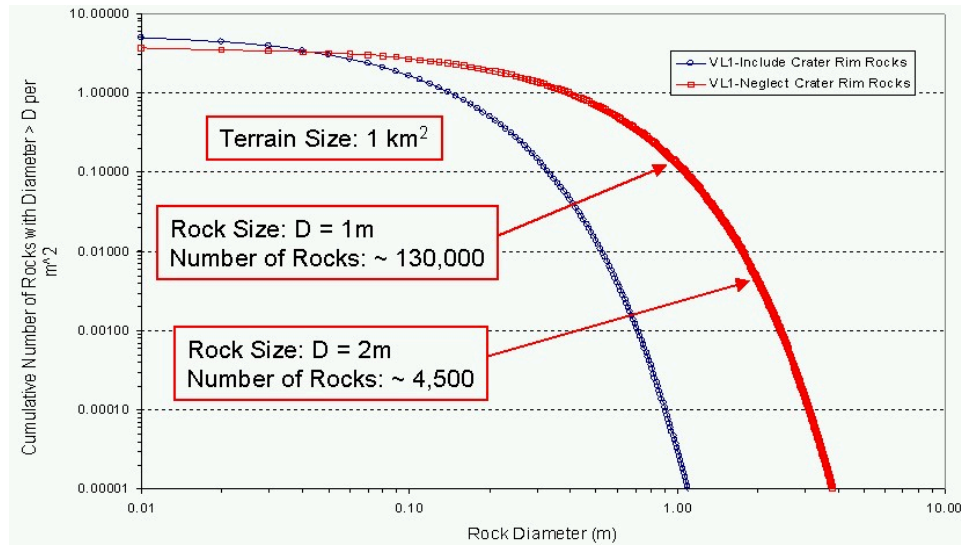


Figure 25. Cumulative number of rocks versus diameter. (Golembek & Rapp: *Size Frequency Distributions of Rocks on Mars*, ref. 11).

From figure 25, it can be seen that on a 1- km^2 terrain, there should be approximately 130,000 1-m in diameter rocks and 4,500 2-m in diameter rocks. The distribution neglecting the crater rim rocks was selected because it allows for higher numbers of large rocks and was well suited for the difficult terrain desired. Computer memory restrictions only allowed a total of 10,000 rocks to be included on the 1- km^2 terrain. This memory consideration is a fundamental issue with the way Vortex[®] is set up and will not allow the modeling of large terrains with large numbers of rocks. As a result, the terrain was restricted to 4,500 rocks of 2-m diameter and 5,500 rocks of 1-m diameter. Figure 26 shows a comparison between a photograph of the actual Viking 1 landing site and the virtual terrain generated within the Tumbleweed simulator.

Winds were modeled at a constant velocity and direction. The velocity chosen was a typical Martian average velocity of 7 m/s. The current version of the Tumbleweed simulator does not account for boundary layer effects.

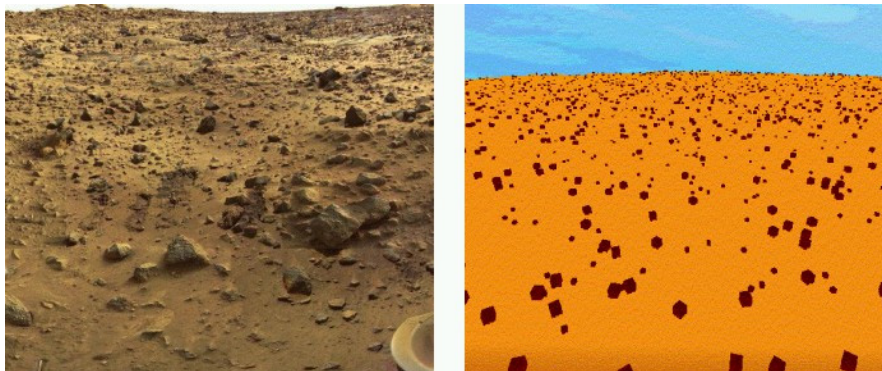


Figure 26. Left, photograph taken by Viking 1 lander. Right, virtual terrain within Tumbleweed simulator modeled after Viking 1 landing site.

5.3.2. Environment Modeling: Identified Improvement Areas

The memory problem present in the current version of the Tumbleweed simulator when generating large terrains with large numbers of rocks is a major restriction to modeling a realistic Mars terrain. The idea of the Tumbleweed concept is to traverse vast and possibly highly rugged areas of the Martian surface. Any mission could potentially cover hundreds, if not thousands, of kilometers. Alternative methods for terrain modeling within the tool will have to be explored. For example, one possible alternative may be to generate only small patches of the terrain as a Tumbleweed rover travels through it. This option would free up memory resources because only small terrain areas would need to be stored at any given time.

Currently, there are limited data describing wind conditions on the Martian surface. Detailed models exist for replicating the environment of the upper atmosphere (Mars-Global Reference Atmospheric Model). The Viking and Pathfinder missions both performed some wind experiments on the surface, but, in general, little is known about the wind profile and boundary layer effects on the surface.

Question 2. Can a realistic Tumbleweed rover be modeled within the simulator?

Tumbleweed rovers were modeled within the simulator for this evaluation. Two different configurations were examined: a 3-m and a 5-m radius rover, both with a mass of 20 kg. Figure 27 shows the comparison between an artist's rendition of one particular Tumbleweed configuration and the virtual Tumbleweed modeled with the Tumbleweed simulator.

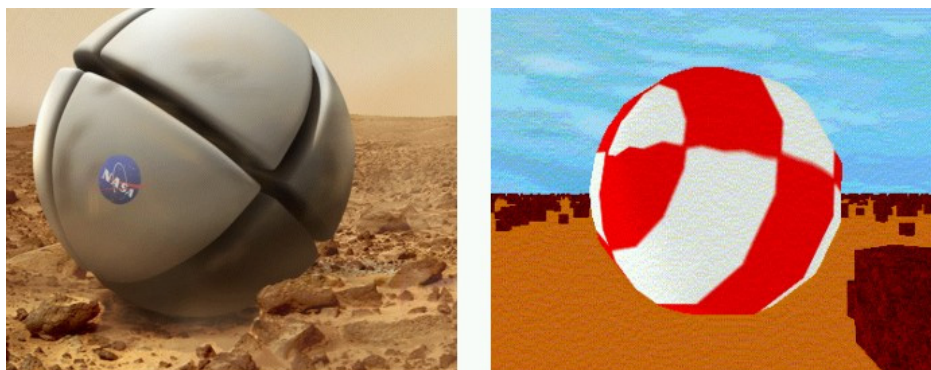


Figure 27. Left, LaRC artists rendition of Tumbleweed rover. Right, virtual Tumbleweed rover modeled within Tumbleweed simulator.

5.3.3. Tumbleweed Modeling: Identified Improvement Areas

The major obstacle to modeling a Tumbleweed rover within the simulator is correctly modeling a flexible structure, or at least the dynamic losses that are associated with a flexible structure impacting and rolling on a nonrigid surface. The current version of the Tumbleweed simulator models the Tumbleweed rover as a rigid body. All impacts are treated as rigid body collisions. The inherent flexibility the structure would actually have is accounted for somewhat by using of a coefficient of restitution. However, dynamic losses due to structural rolling resistance, which is identical to the rolling resistance discussed in section 5.2.1, are not accounted for. To truly replicate the motion of a Tumbleweed rover, these dynamic losses will need to be accounted for in future analysis tools. High fidelity, finite element tools exist that can accurately model impacts. However, these tools are highly taxing on computational resources and are

simply impractical for Monte Carlo type simulations. Alternative methods will need to be explored that can approximate the dynamic behavior of a Tumbleweed rover. One possibility might be to use a simplified modeling approach, which incorporates simple physics relationships in parallel with empirical test data to apply correctional “fudge factors” to the tool.

Additionally, there are two other areas that the simulator should improve in regarding Tumbleweed modeling. First, the coefficient of drag of the Tumbleweed is hard coded into the current version as that of a sphere at low Reynolds numbers ($C_D = 0.5$). As already discussed in the aerodynamics section, many of the current designs have much higher coefficients of drag ($C_D > 1.0$). Being able to vary the drag coefficient of the rover within the Tumbleweed simulator will be required to analyze these other configurations.

Question 3. Can anything be learned about the dynamic behavior of the Tumbleweed rover from the tool in its current state of development?

With the terrain and Tumbleweed rover modeled within the simulator to the best of its current ability, the next step in the evaluation was to set up and run a series of Monte Carlo simulations to take a preliminary look at the dynamic behavior of a Tumbleweed rover. The two rovers (3- and 5-m radius) were run simultaneously over the simulated terrain, with an initial separation of approximately 300 m to avoid Tumbleweed-to-Tumbleweed collisions. Their initial positions were slightly varied with each Monte Carlo iteration so that the path each rover took across the terrain would be different for each run. The simulation consisted of 2000 iterations.

Figure 28 shows the path taken across the simulated Viking terrain by one Tumbleweed rover over a 120-s time interval. The blown-up area shows a segment of the Tumbleweed’s path where there was an impact with a rock. The rover is thrown in the opposite direction as a result of the collision until eventually it resumes its movement in the downwind direction.

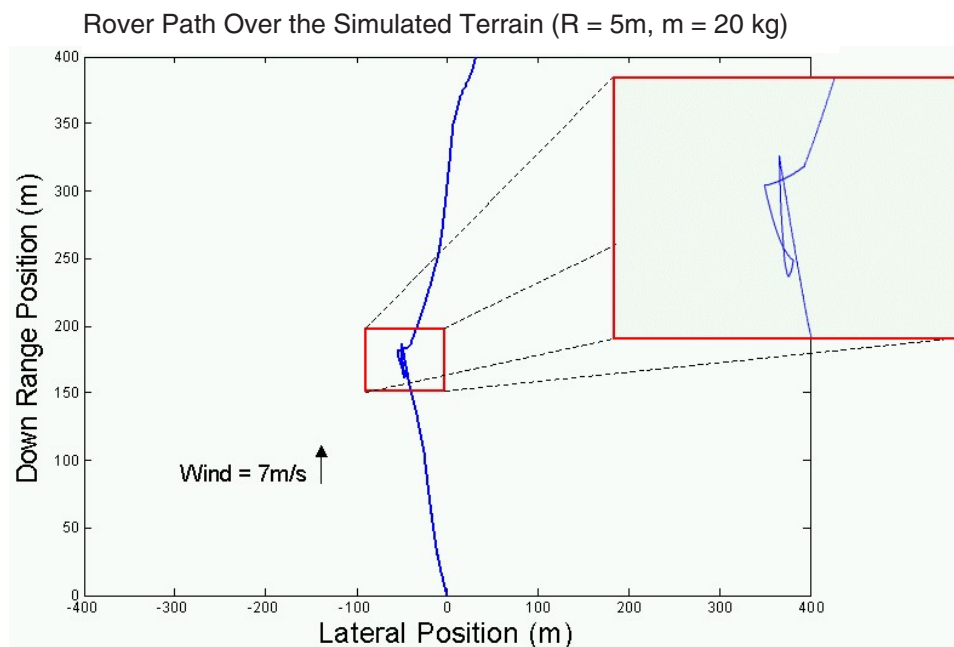


Figure 28. Tumbleweed rover path from one Monte Carlo run, 120 s.

Figures 29 and 30 show the distribution of the 2000 Tumbleweed runs over the simulated terrain during a 120-s time interval for the 3- and 5-m radius rovers, respectively. Each point represents the location of the rover on the terrain at the end of 120 s. In the case of the 3-m radius Tumbleweed, the data are fairly uniformly scattered, with most of the rovers being located 100- to 250-m downrange. For the 5-m radius Tumbleweed, one would expect the scatter to look similar to that of the 3-m Tumbleweed, with the only major difference being that the larger diameter rovers would, on average, be able to move further downrange in the same 120 s. Looking at figure 30, this is seen to some degree, but not as much as would be expected. Additionally, it can be seen that there are some strange concentrations of stuck Tumbleweeds in the first 150-m downrange.

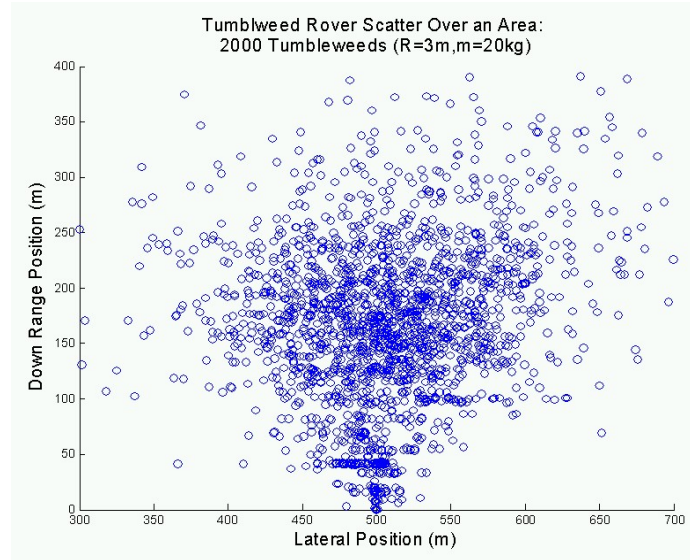


Figure 29. Tumbleweed distribution over simulated terrain (3-m radius).

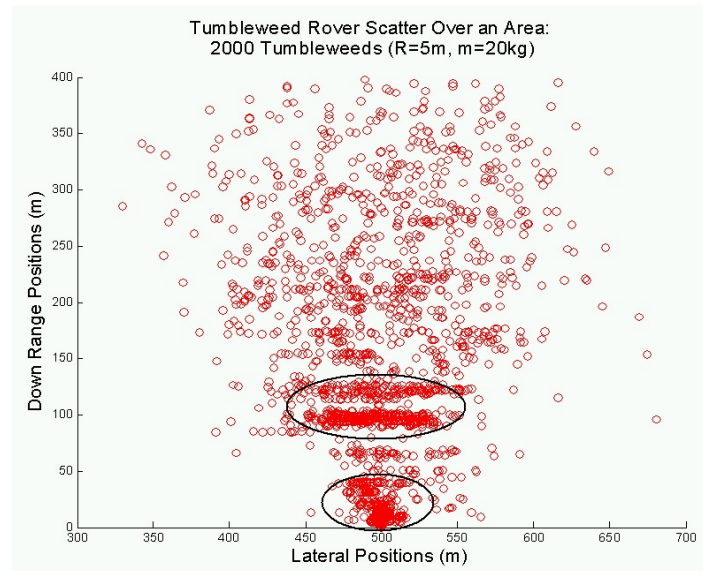


Figure 30. Tumbleweed distribution over simulated terrain (5-m radius). Concentrations are within the circled regions.

Figure 31 displays histograms of the distributions over the simulated terrain for the 3- and 5-m radius rovers. The concentrations of the 5-m radius rovers discussed previously become even more apparent when looking at the histograms. For the 3-m radius Tumbleweed, approximately 360 of the 2000 (18 percent) iterations performed show the rover to be located 0 to 100 m downrange after 120 s. For the 5-m radius Tumbleweed, approximately 890 of the 2000 (45 percent) iterations are located in the same downrange region over the same time interval.

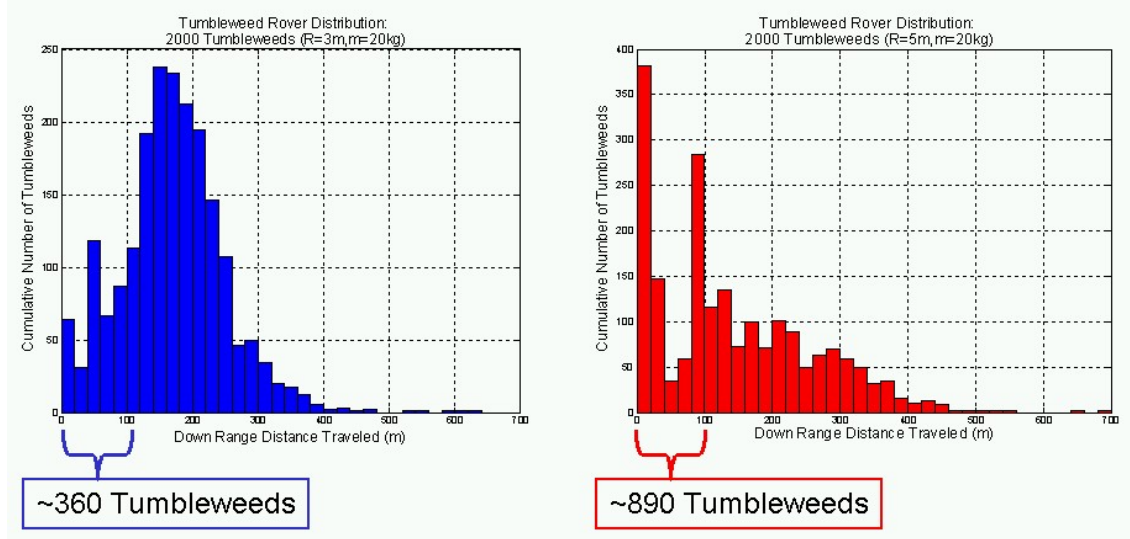


Figure 31. Tumbleweed rover distribution histograms.

One possible hypothesis for this discrepancy is directly related to the parameters selected for the simulated terrain within the Tumbleweed simulator. Recall from question 1 that the terrain defined was 1 km² with a total of 10000 randomly placed 1- or 2-m cubic rocks. On average, it works out to be approximately 1 rock every 10 m. Coincidentally, 10 m is also the diameter of the larger Tumbleweed rover.

There are two basic ways in which a Tumbleweed rover can navigate past a rock: one is to go around it, and the other is to go over it. From a static analysis viewpoint, the 7-m/s wind used in the simulation is not sufficient to push either of the Tumbleweed rovers over any of the 1- or 2-m rocks. In other words, recalling equation (1) from section 5.2.1, for 3- and 5-m radius Tumbleweeds in a 7-m/s wind, M_{F_w} will always be less than the sum of M_W and M_{N_o} . As a result, assuming the Tumbleweed is starting from rest, to navigate through the simulated terrain the rovers will have to go around the rocks. As can be seen in figure 32, the 3-m radius Tumbleweed has a distinct advantage due to its smaller size for navigating around and between the rocks of this particular terrain. From a dynamic standpoint, the initial velocity (V_i) of the rover, its radius, and the size of the rock it is impacting will determine whether or not the collision will result in the rover's bouncing up and over the rock or up and in the opposite direction from which it originally came. More specifically, for the rover to bounce up and over the rock θ_T , the post impact trajectory angle of the Tumbleweed (fig. 23) would have to be less than 90°, and the post impact bounce height would have to be higher than the height of the impacted rock.

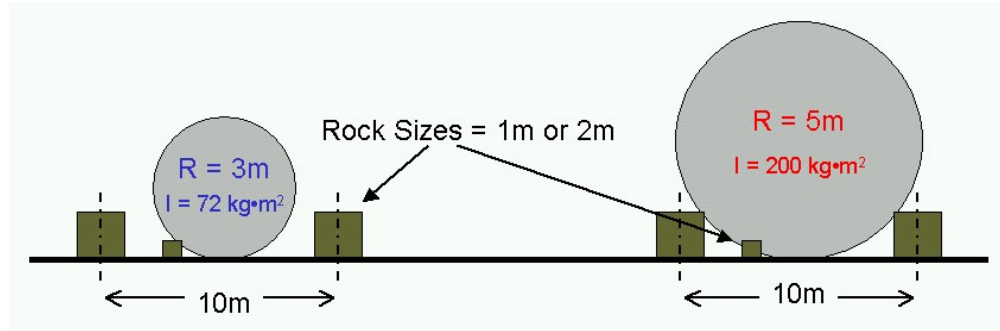


Figure 32. Static perspective showing how 3-m Tumbleweed can navigate simulated terrain better than the 5-m Tumbleweed. Inertias assume a uniform density sphere.

Using the assumptions and equations discussed in section 5.2.2 regarding impact analysis, the dynamic conditions required for going over the top of a given rock can be approximated. The calculations were carried out for the rock sizes and Tumbleweed rover configurations used in this evaluation and are summarized in table 5.

Table 5. Requirements To Overcome 1- and 2-m Cubic Rocks Dynamically

Rock size, m	3-m radius Tumbleweed		5-m radius Tumbleweed	
	θ_T , deg	V_i , m/s	θ_T	V_i , m/s
1 x 1 x 1	93	NA	71	~3
2 x 2 x 2	140	NA	103	NA

From table 5, it can be seen that of the 3- and 5-m radius Tumbleweeds, the 5-m rover is the only one of the two that can dynamically conquer the rocks on the simulated terrain, but only the 1-m rocks. The 5-m Tumbleweed would need an initial velocity of approximately 3 m/s to bounce up high enough to go over top of the 1-m rock. For the other cases, θ_T is always greater than 90° . As a result, it does not matter what initial velocity they have before the collision, the rovers in these cases will always bounce back in the opposite direction from which they came; thus, the velocity for these cases is defined as “not applicable” (NA) in table 5.

From the preliminary analysis discussed previously, a hypothesis can be generated that would suggest that because of the properties of this particular simulated terrain and the chosen configuration of the Tumbleweeds, the 3-m radius rovers are more efficient at navigating through the rock field than the 5-m radius rovers. In the first 100- to 150-m downrange, the 5-m radius Tumbleweeds might not have sufficient time to accelerate to the 3 m/s necessary to bounce up and over the 1-m rocks. As a result, they will bounce backward and eventually become lodged, as shown in figure 32, much more frequently than the 3-m radius rovers. Even though the 3-m radius rovers cannot ever bounce up and over any of the rocks in this terrain (because the relationship between the dimensions of the rocks and the rover will never allow θ_T to be greater than 90°), they will always have an easier time going around the rocks laterally simply because of their smaller diameter.

It is important to reiterate that this analysis is preliminary and effects of rock sizes on Tumbleweed navigability will obviously need to be looked at in more detail. However, this analysis has yielded an interesting result that might not have been noticed unless a Monte Carlo type simulation was studied. A

preliminary conclusion can be drawn about the relationship between Tumbleweed size and terrain navigability that, at the very least, challenges the intuitive assumption that bigger Tumbleweeds with higher surface areas are always better at achieving maximum downrange distance. In fact, this analysis shows that on a preliminary level, it may actually turn out that the optimal Tumbleweed size is highly dependent on the properties of the terrain it is intended to traverse.

5.4. Development of Two-Dimensional (2-D) Simulation

Development continues on an in-house dynamics analysis tool, a MATLAB/Simulink physics-based simulation. The simulation incorporates translational and rotational dynamics, wind forces acting on the Tumbleweed rover, a simplified mass/spring flexible structure model, and ground contact effects, such as friction and rolling resistance (fig. 33). The current model considers two-dimensional planar motion; development efforts in FY2004 will focus on refinement of the current modeling assumptions and extension of the model to three-dimensional motion. This simulation will provide an understanding of the range of Tumbleweed design parameters that are important for mobility over Martian terrain. The in-house simulation tool has been developed with an emphasis on providing ease of model customization to perform dynamic mobility studies of novel concepts for both passive and actively controlled Tumbleweed rovers.

Empirical tests were performed to evaluate modeling assumptions used in the MATLAB/Simulink physics-based simulation. The model demonstrated the ability to predict rolling motion on an inclined plane and vertical bouncing, including structural damping effects (see section 5.5). Work is ongoing to refine the model to better predict the sliding-to-rolling transition during structural deformations that result from impact during bouncing. The planar motion simulation tool has been used to perform some initial dynamics studies.

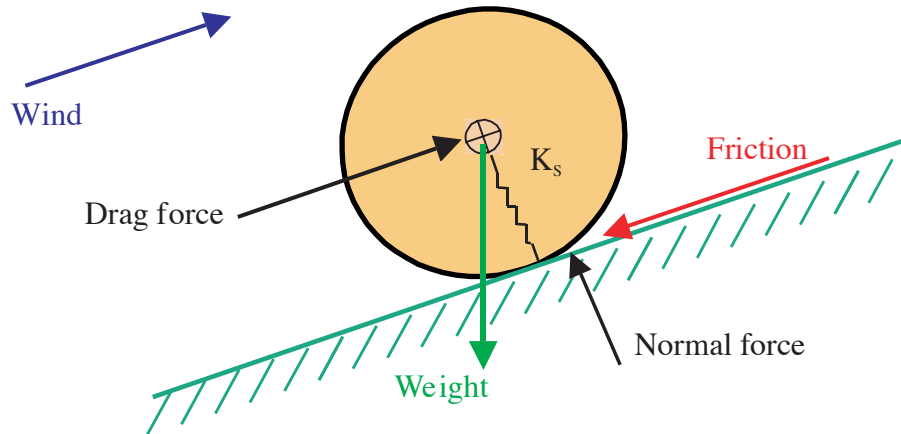


Figure 33. Tumbleweed on sloped terrain.

5.4.1. Rolling Motion Along Sloped Terrain

The planar motion simulator described in section 5.4 was used to perform a study of the steady-state rolling velocity of a flexible Tumbleweed on a sloped terrain. A range of Tumbleweed design parameters was studied, including mass, size, drag coefficient, and rolling resistance. Results of steady-state rolling speed versus wind speed for a range of terrain slope conditions were determined by using a representative Mars gravity constant (3.7 m/sec^2) and surface atmospheric density (0.0155 kg/m^3). Figures 34 and 35 demonstrate the effect of a rolling resistance coefficient on the steady-state rolling velocity for a set of

representative Tumbleweed design parameters. The Tumbleweed mass (10 kg) and overall radius (3 m) were selected based on estimates from previous feasibility studies (ref. 1). The aerodynamic drag coefficient was set equal to an approximate value for a smooth sphere ($C_d = 0.5$). This value serves as a lower bound on the range of drag coefficients obtained from wind tunnel tests in the BART facility of representative Tumbleweed configurations (see section 4.2.2). The range of rolling resistance coefficients was based on values for tires with low inflation pressures over a range of surface conditions. Figure 34 shows the steady-state rolling velocity versus wind speed for a rolling resistance of 0.05, which is an approximate lower bound for a medium hard road surface. Figure 35 shows the rolling velocity for a rolling resistance of 0.15, which is an approximate lower bound for loose sandy surfaces. These values were considered within the range that would be expected over various Martian surface conditions.

The results from this study can be used to estimate the effect of rolling resistance on mobility over a range of Martian terrains and wind conditions. As can be deduced from figures 34 and 35, a lower value for rolling resistance implies a relatively small range of wind conditions in which the Tumbleweed will remain stationary on a given terrain slope. For rolling resistance of 0.05, the Tumbleweed point design considered requires wind speeds >7 m/s to climb terrain and wind speeds >4 m/s to maintain position on a slope of 5° . As the rolling resistance is increased to 0.15, the wind speed required for climbing the 5° slope increases to 9 m/s, while a downslope motion (i.e., negative velocity) is prevented for any wind with an upslope component (positive velocity).

The results from this type of simplified analysis can be used to determine Tumbleweed design sizing requirements for accomplishing mobility objectives under the assumption that Tumbleweed mobility is dominated by rolling. Local topography slopes and wind conditions that can be defined and/or bounded for selected Mars sites may then be used to derive design requirements and site selection. Airborne motion resulting from rock/terrain impacts may affect downrange mobility estimates as well as produce the potential for crosswind trajectory dispersions. Impact dynamics during subsequent Tumbleweed bouncing may also affect mobility estimates. Higher fidelity dynamics models should be developed in follow-on studies to assess the effect of bouncing transients on Tumbleweed mobility estimates.

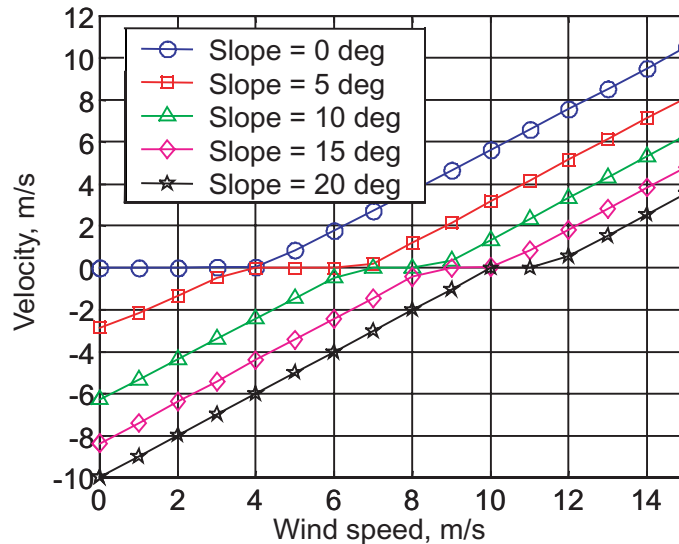


Figure 34. Steady-state rolling velocity versus wind speed and terrain slope angle. Radius Tumbleweed = 3 m, $C_d = 0.5$, Rolling resistance coefficient = 0.05.

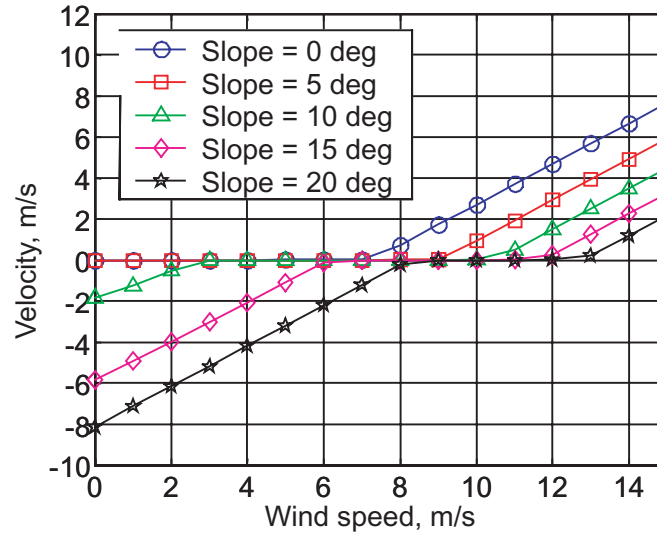


Figure 35. Steady-state rolling velocity versus wind speed and terrain slope angle. Radius Tumbleweed = 3 m, $C_d = 0.5$, Rolling resistance coefficient = 0.15.

5.5. Using Simple Empirical Tests for Two-Dimensional (2-D) Simulator Validation

Empirical tests were performed by using spherically shaped objects of various sizes to evaluate the modeling assumptions used in the MATLAB/Simulink physics-based simulation test bed (fig. 36). Based on the test results, the model demonstrated the ability to predict rolling motion on an inclined plane and vertical bouncing, including structural damping effects.

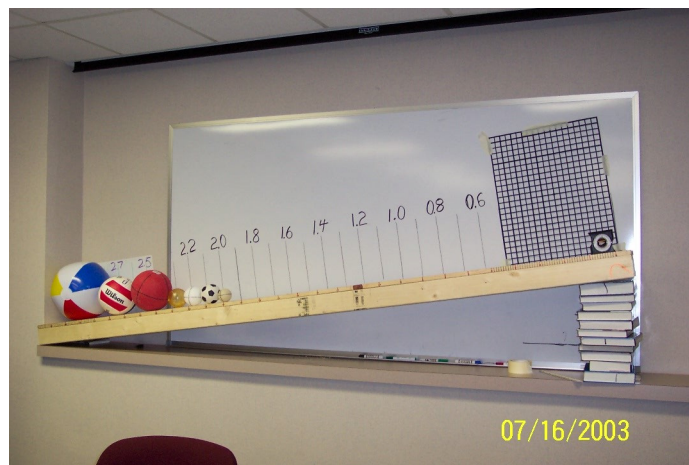


Figure 36. Test setup for simple empirical tests.

The primary objectives of the simple empirical tests were the following:

- Measure Tumbleweed model parameters:
 1. Using known weights for loading and calipers for model deformation determine structural stiffness, including range of linear response.
 2. Contact patch under weights. Verify dynamics model assumptions relating to contact patch size, Tumbleweed deformation, and stiffness.

3. Rolling resistance coefficient (from pending motion on inclined ramp). Determine corresponding offset normal force location as a percentage of contact patch length.
- Conduct dynamics tests of model rolling and bouncing motion on inclined ramp:
 1. Use video to capture dynamics.
 2. Verify equilibrium rolling rate and velocity from simulation.
 3. Determine dynamic rolling resistance. Compare with value obtained from test and values used in simulation.
 4. Determine corresponding offset normal force location as a percentage of contact patch length.
 5. Measure position along ramp. Compare with simulation results.
 6. Investigate dynamics during initial impact. Derive angular acceleration and rates from video analysis. Determine structural damping.
 7. Does rolling resistance dominate motion during initial impact?
 8. Is sliding-to-rolling transition consistent with assumptions in simulation?

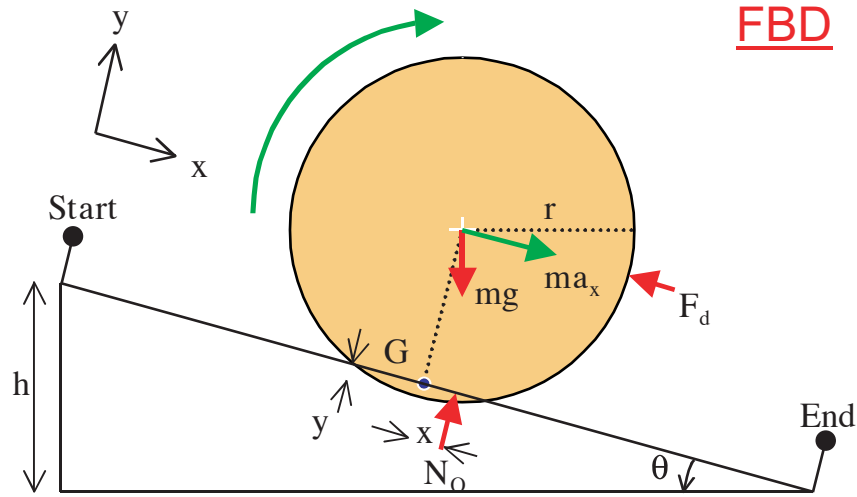


Figure 37. Flexible sphere rolling down ramp.

Figure 37 shows a free body diagram of the simple empirical tests, with the Tumbleweed approximated by a flexible sphere rolling down a ramp. The sum of the moments about point G is given by equation (15):

$$\sum M_G = 0 \Rightarrow mg_x(r - y) + I\alpha = mg \sin \theta(r - y) - N_O x - F_d(r - y) \quad (15)$$

where

$$x = \sin \theta(r - y) - (a_x/g)[(7/5)r - y] \quad (16)$$

and the Coefficient of Rolling Resistance (CRR) is defined as

$$\text{CRR} = x/r \quad (17)$$

The torque produced by the drag force was neglected for simplicity. The general effects of rolling resistance can be gauged by evaluating the magnitude of the offset normal force (N_O) torque. The significance of rolling resistance and stiffness/damping characteristics on a bouncing model can also be evaluated with this test configuration.

For the tests, a volleyball, bouncy ball, beach ball, Styrofoam® ball, two (2) foam balls of different densities, and a stereolithography (SLA) ball were used as the test models. A drag coefficient of 0.5 was assumed for all balls because they were spherical.

First, basic structural parameters of the test balls were measured for incorporation in the simulation model. A digital scale was used to measure each ball's mass, and calipers were used to measure each ball's diameter. The percentage of each ball's radius that it deformed under its own weight was determined by placing each ball on a flat glass surface and measuring the length of the contact patch. The amount of deformation of the radius can then be derived from the contact patch measurement. This measurement was performed to estimate the ball's stiffness and to verify the contact patch calculation used in the simulation model. Equation (18) shows the relationship of Tumbleweed deformation to contact patch length:

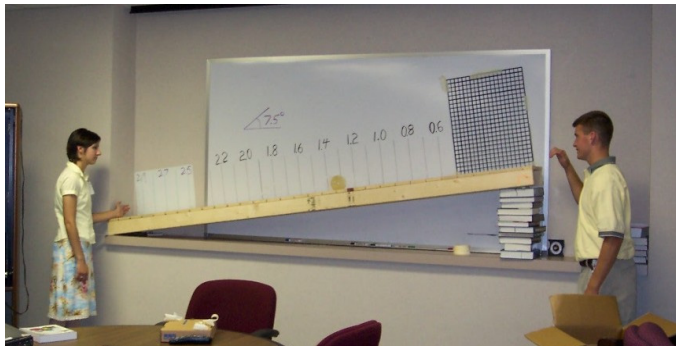
$$l_c = [4\delta(2R_t - \delta)]^{1/2} \quad (18)$$

where δ is the deformation of the Tumbleweed measured along the radius R_t , and l_c is the length of the contact patch (note: l_c is a sector length, assuming a circular shape for the Tumbleweed outer surface). In a static test, each ball was placed on a flat glass surface. Known weights were added to each ball, and the contact patch was measured. From this measurement, the deformation of the radius was calculated and could be compared to the imposed loading to determine each ball's stiffness.

Next, dynamic and static tests (fig. 38) were conducted to determine the rolling resistance and the relationship to the normal force offset distance from the Tumbleweed's center of gravity. To determine the offset normal force for a static condition and hence the rolling resistance, the balls were placed on a board of known length. The board was raised until the balls began to roll (fig. 38(a)). To determine the offset normal force in a dynamic condition, the balls were placed on a sloped board with a small initial velocity, and the board was lowered until the balls stopped rolling. The vertical height of the board in both cases was measured, and the angle of the slope at which the ball started to roll or stopped rolling was calculated. By using the following equation the distance to the offset normal force (D_n) was calculated:

$$D_n = \tan \theta * R_\delta \quad (19)$$

where θ is the angle at which the model starts to roll or stops, and R_δ is the deformed radius of the model.



(a) Determination of offset normal force.



(b) Determination of damping ratio.

Figure 38. Simple empirical testing.

The damping ratio of each ball was determined from dropping the balls with no initial velocity from a known height onto a flat surface (fig. 38(b)). Behind the balls was a grid to measure the height of each bounce. A camera taking 30 frames per second videotaped all dynamics tests. The frame number for the peak of each bounce was used to calculate the elapsed time between bounces. The parameters of each ball and a 0° slope angle were input into the simulation test bed model. The damping ratio used in the model was tuned until the model was able to match the height of the test bounces in the same amount of time.

Finally, a series of dynamic tests of rolling and bouncing motion on the sloped ramp were conducted for validation of model assumptions. Three sets of dynamics tests were conducted. Each of the dynamics tests was conducted on a board 3 m long at inclinations of 5° , 7.5° , and 10° . The board was marked at 10-cm intervals down the length of the board, and at 1 cm intervals for the first 50 cm of the board. Behind the first 50 cm of the board was a 1-in. square grid. In the first dynamics test, each ball was rolled down the inclines. From the videotape, the time elapsed for each ball to roll down the length of the board was determined and recorded at 20-cm intervals. In the second test, the balls were dropped from varying heights in front of the grid. The time elapsed for each ball to roll down the board was determined and recorded at 20-cm intervals as before. The vertical positions of each ball were also recorded before the ball was dropped and when it crossed the 20- and 40-cm marks down the board. In the third test, the balls were dropped at varying heights. The vertical and horizontal positions and the time elapsed were recorded at the peak of each bounce and at each impact with the board until the ball had traveled 50 cm down the board.

Measurement of the angle at which the balls began to roll and the angle at which the balls stopped rolling when given a small initial velocity showed that the static rolling resistance was greater than the dynamic rolling resistance. The rover model needs to be modified to include this effect. It currently assumes that the rolling resistance at impending motion is the same as the rolling resistance when it is in a dynamic condition.

The static test showed that the model assumption of linear stiffness appears valid. Results of the deformation of each ball, with varying loads, are shown in figure 39. Several vertical drop tests were conducted on a flat surface for each ball to determine damping, as described previously. Figure 40 shows

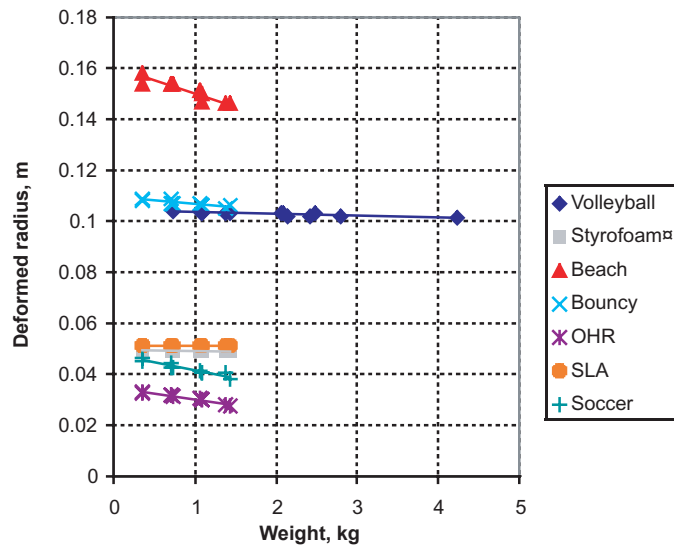


Figure 39. Deformation of radii of test balls under varying weights.

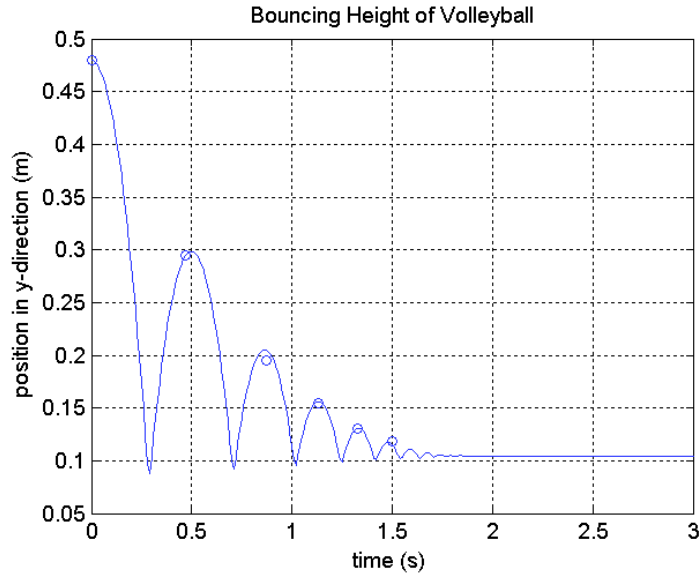


Figure 40. Bouncing height of volleyball.

a typical test result for the volleyball, as compared to the results from the simulation after tuning the damping ratio. The circles represent the test data and the curves are the simulation results after tuning. Since the model could predict the bounce height of the balls when dropped on a flat surface, the linear damping assumption also appears to be valid.

For a rolling case, the model could predict the test balls' downrange motion when the values for the offset normal force were tuned. As the slope angle increased, the percent offset normal force generally increased, which, in turn, increased the rolling resistance. Several rolling tests for each ball were conducted on a sloped surface to determine the effective dynamic rolling resistance. Figure 41 shows a

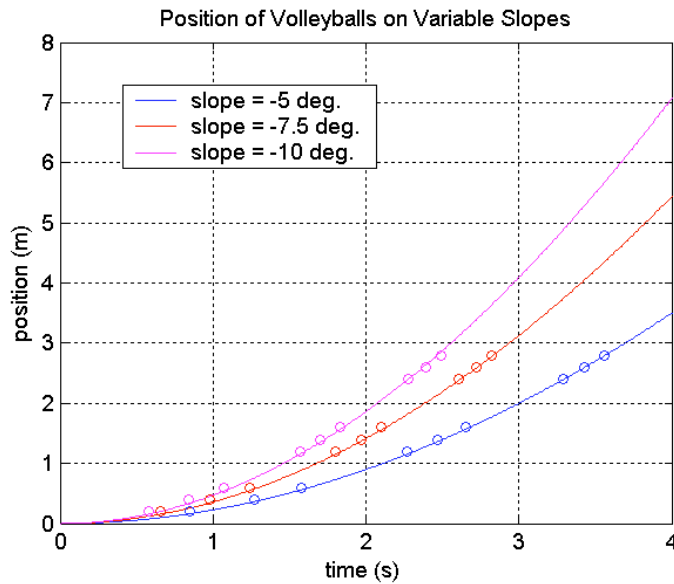


Figure 41. Position of volleyballs on variable slopes.

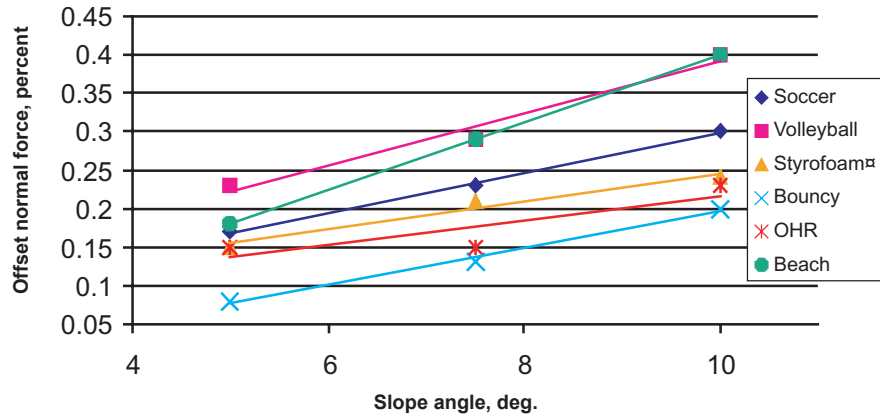


Figure 42. Percent offset normal force versus slope angle.

typical result of the downrange position for the volleyball rolling test when compared to the simulation results after tuning the rolling resistance for each slope angle. The circles represent the test data, and the curves are the simulation results after tuning. Figure 42 shows the tuned values of offset normal force for each ball for all tests. It was determined from these results that there seemed to be a near linear relationship between slope angle and the offset normal force. The tuned results are shown, along with a best linear fit for each ball in figure 42. This effect of increased offset normal force may result from deformations of the Tumbleweed contact patch due to increased gravity loading along the direction parallel to the ramp as the slope increases. This hypothesis seems to explain the results; however, further work is needed to verify this assumption.

In a bouncing case, although the simulation model could predict the bounce height of the balls, it underpredicted the downrange motion because the rolling resistance had a dominant effect for each impact. The test results showed that the downrange velocity of the test balls was not decreased by each impact, which contradicted the simulation results. The vertical position versus downrange motion for selected tests of the beach balls is shown in figure 43.

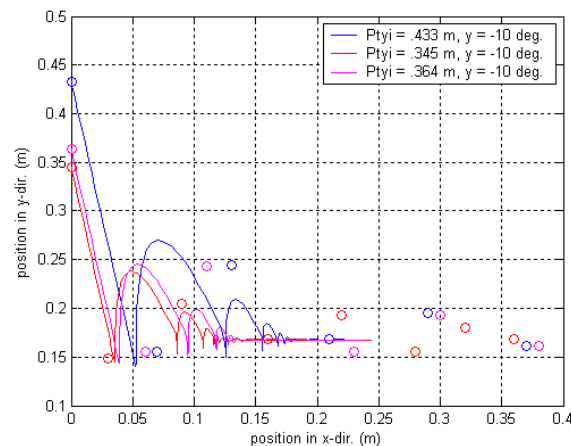


Figure 43. Trajectory of beach balls.

Further analysis needs to be conducted of the impact during bouncing to verify the assumption regarding the transition from sliding-to-rolling. The assumptions of linear stiffness and damping appear to be valid. The model can predict downrange motion of the Tumbleweed when it is in a rolling condition but not when it is bouncing. Further analysis of why the model cannot predict a bouncing trajectory also needs to be conducted to correct this problem before the Tumbleweed simulation test bed can be extended to six degrees of freedom and a terrain model can be added.

6. North Carolina State University Tumbleweed Prototype

6.1. Overview of the Box Kite Tumbleweed Earth Demonstrator

In addition to the wind tunnel testing described in section 4.2.1, undergraduate students from the NCSU senior aerospace design class also researched, designed, and analyzed the Tumbleweed rover concepts shown in figure 7 and ranked the concepts based on the criteria shown in table 6. The Box Kite was chosen as the most appropriate design for further development. The choice was based on these results and was later modified by adding hoops to improve rolling characteristics (fig. 44).

Table 6. NCSU Selection Criteria

Name and score		Drag	Major parts	Mass
Tumblecups	16.67	6.70	8.78	1.19
Box Kite	23.54	10.00	10.00	3.54
Balloons	19.27	6.23	10.00	3.03
Dandelion	23.36	6.63	6.72	10.00

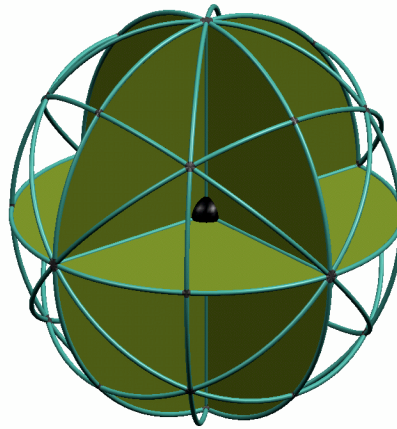


Figure 44. NCSU Box Kite.

The NCSU students designed and built a Tumbleweed Earth Demonstrator (TED) of the Box Kite concept (fig. 45) and presented their design, along with their associated research at NASA LaRC, as part of a National Institute of Aerospace (NIA) Seminar (fig. 46). NCSU also involved 6th graders in an education outreach activity with Tumbleweed (see section 8.0). A mass breakdown of the TED vehicle is provided in table 7.



Figure 45. TED debut at NCSU picnic May 9, 2003.



Figure 46. TED presented at the LaRC Reid Conference Center May 14, 2003 (LaRC BART Jr. providing the wind).

Table 7. TED Mass Breakdown

Components	Mass, g current best estimate	Contingency		Total mass, g
		Percent	Mass, g	
Core	1752.60	5	87.63	1.19
Sails	488.58	2	9.77	3.54
Core bungee assembly	876.00	2	17.52	3.03
Ring structures	7200.00	5	360.00	10.00
Total for TED, kg				10.79

6.2. TED Instrumentation and Systems

The TED core (fig. 47) is a resin shell created by Fineline Prototyping, Inc. that protects the payload from the environment and provides attachment points for the sails and outer rings and an access hatch for the payload. The instrumentation payload consists of biaxial accelerometers, environmental sensors (pressure and temperature transducers), an imager, and a Global Positioning System (GPS) tracking device. The core also contains the data handling and communication system, which is a commercially available unit for amateur rocketry.

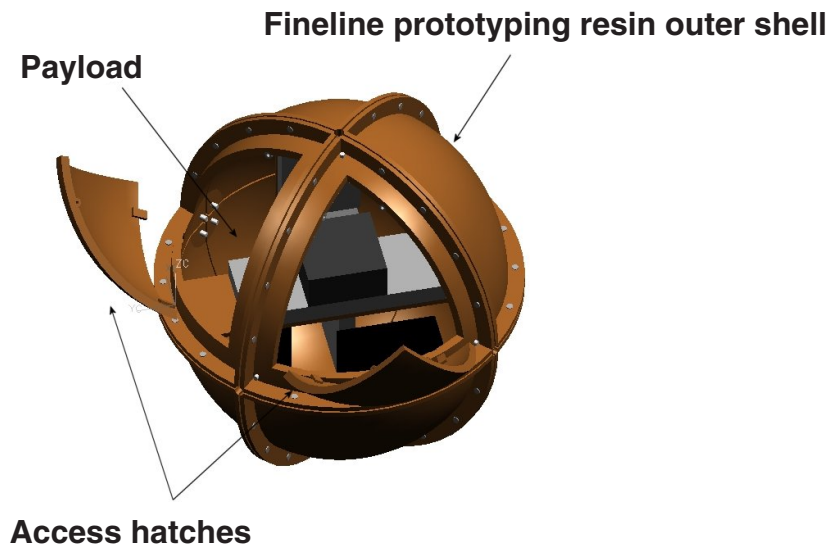


Figure 47. TED payload core.

7. Outreach

Outreach is a process that displays the accomplishments of NASA and inspires students to investigate science and technical careers. The Tumbleweed rover concept catches the imagination of people of all ages and educational levels.

The Mars Tumbleweed was featured in a number of outreach activities in FY03. The LaRC Public Services Office, Office of External Affairs, requested a Mars Tumbleweed exhibit for the 2002 Virginia State Fair. The Mars Tumbleweed display, with a simulated Mars rock field, was later used for other outreach demonstrations, including the Jones Magnet School Planetarium, Langley Career Days (fig. 48), LaRC Take Your Children to Work Day, and the Virginia Air and Space Center (VASC) Robotics Camp.



Figure 48. The Mars Tumbleweed display.

Jennifer Keyes spoke at the New Horizons Governor School about Mars Exploration on July 24, 2003 to two groups with about 40 students each, the first had 4th and 5th graders and the second 3rd and 4th graders. The presentations consisted of a Microsoft PowerPoint presentation and an interactive activity in which students were arranged into small groups and used materials ranging from toothpicks to Playdoh® to rocks. Each group designed its own rover. Each student received a certificate at the end of the event.

Student participation at LaRC for FY03 included Rachel Owens, a Langley Aerospace Research Summer Scholar (LARSS) from Virginia Polytechnic Institute and State University, who performed dynamics modeling and testing of Tumbleweed rovers. Michael Wisniewski from the University of Michigan, Ann Arbor, was also a 2003 LARSS intern, researching electrical power system concepts for the Tumbleweed rover. Additionally, Heidi Owens, a student at Bethel High School, Hampton, Virginia, and one of the counselors at the Virginia Air and Space Center (VASC) Robotics Camp, joined the Mars Tumbleweed Science team through the New Horizons Governor's School for the Science and Technology Mentorship Research Program. Her research project, "Instrumentation on a Mars Tumbleweed Rover to Detect Astrobiological Life Forms," concluded in May 2004.

The sixth grade science classes of Carnegie Middle School in Raleigh, North Carolina participated in an outreach program through their teacher Holly Hanrahan, a Kenan Fellow at NCSU. By working with the Aerospace Engineering senior design class at NCSU (fig. 49), the Carnegie students learned about aerodynamics, structures, and other engineering disciplines needed to build planetary exploration systems. Ms. Hanrahan and Dr. Fred DeJarnette presented their collaborative Tumbleweed Project at the International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science in Lisbon, Portugal on October 9, 2003 (refs. 12 and 13). Ms. Hanrahan also gave a lecture on the Tumbleweed at the North Carolina State Teachers Association conference on November 13, 2003.

The Mars Tumbleweed rover was featured extensively in the news media during 2003—The LaRC Researcher News (5/23/03), the Richmond Times-Dispatch (5/17/03), Space News (5/26/03), www.space.com, www.marstoday.com, and www.spaceref.com. Articles have also been included in the NC State Extension and Engagement magazine, the Raleigh News and Observer, the Wake County (NC) Public Schools newsletter, and the county's magnet school newsletter. Holly Hanrahan and the students participated in a live webcast to discuss their Tumbleweed activity. A television sequence for NASA's Destination Tomorrow™, program 13, features the Mars Tumbleweed rover.



(a) Testing Tumbleweed designs in a wind tunnel designed on the spot by the Carnegie students.



(b) Working with NCSU students on the TED.

Figure 49. Carnegie Middle School students.

8. Concluding Remarks

8.1. Summary

NASA LaRC is studying concepts for a new type of rover known as a Mars “Tumbleweed,” that would derive mobility through use of the Martian surface winds. The “Search for Life” goal was identified as the most scientifically interesting and challenging mission for the Tumbleweed concept. Significant progress was made in FY03 in defining power system options, structural materials, communication architectures, and deployment options. The first wind tunnel tests of LaRC Tumbleweed concepts were completed by using the Langley Research Center Basic Aerodynamic Research Tunnel (LaRC BART). Progress was made on the development of a Tumbleweed simulation capability and an extensive test of the Monte Carlo simulation capabilities was conducted. Empirical tests were also performed using spherically shaped objects of various sizes to evaluate the modeling assumptions (e.g., rolling resistance) used in the simulation. And finally, the North Carolina State University (NCSU) senior Aerospace design class designed, built, and tested a Tumbleweed Earth Demonstrator (TED) of the Box Kite Tumbleweed concept.

8.2. Plans

The study areas initiated in FY03 will continue to be addressed in FY04 at a greater level of detail:

- Science Mission Definition
- System Definition and Analysis
- Dynamic Modeling and Analysis
- Aerodynamic Modeling and Analysis
- Collaboration with universities and Public Outreach

Working with Mars program scientists, the science objectives will be refined and specific mission scenarios will be defined. Areas where recent outflow of water may have occurred (e.g., canyons and

crater walls) and areas where water may have flowed in the distant past will be identified. Micro-instrument technologies that are applicable to the search for life mission will be identified. Subsystem technologies identified in FY03 will be applied in system trade studies to determine the advantages and disadvantages of particular options for power, communications, structures and materials, and navigation.

The simulation test bed will be modified to incorporate additional analysis capabilities and move to a Mars terrain-based simulation, incorporating terrain generated from Mars Orbiter Laser Altimeter (MOLA) data. Emphasis will be on development of a 3-D test bed to simulate a virtual Tumbleweed mission. Sophisticated empirical testing will be conducted, building upon the knowledge gained in the simple empirical tests already conducted and which are necessary for further refinement of analytical models and validation of modeling assumptions.

Analysis of BART test data will continue, including development of Reynolds number comparisons and analysis of the effects of differing model frontal areas. Data from the TTU ABL tests will also be analyzed, and results of all aerodynamic tests will be incorporated into the simulations. Options for achieving lower Reynolds number testing will be investigated, including use of higher sensitivity balance or University facilities. The Tumbleweed concepts will be refined for follow-on testing in the BART, and the use of facilities capable of producing a Mars relevant environment will be investigated. Collaboration efforts with NCSU and Texas Tech University (TTU) will continue, and additional collaborations will be pursued, including the development of collaborative robotics/swarming algorithms with Case Western Reserve University and the use of the Carnegie Mellon University inflatable robotic rover test bed for dynamic testing.

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Appendix A. MEPAG Search for Life Goal: Objectives, Investigations, Measurements, and Example Instruments for Tumbleweed

MEPAG Objective/ Investigation	MEPAG measurement	Example instrumentation	Mass, kg	Power, W	Data	Ref.	Comments	Tumbleweed control capability
Determine if life exists today— <i>Carry out in situ exploration of areas suspected of harboring liquid water</i>	For at least 20 stations at 4 targeted sites, conduct <i>in situ</i> geophysical and chemical searches for subsurface water and other volatiles over km ² surface	Water detection	0.06	1.5	TBD	14	Deep Space 2 evolved water experiment—Tunable Diode Lasers (TDL)	None/ Simple ¹
		Gas chromatograph/Mass spectrometer	4.0	8 15 peak	2.5 Mbit max 0.6 Mbit min	15		
		X-ray diffraction X-ray fluorescence	< 5	< 10	TBD	16		
		Laser Raman spectrometer	1.5	1.1 2.5 peak	TBD	15, 17		
Assess the extent of prebiotic organic chemical evolution— <i>Search for complex organic molecules in rocks and soils</i>	In situ/mobile platforms deployed to at least 3 well-characterized and diverse sites to assess the mineralogy,...	Mossbauer spectrometer	0.5	1.6	1.2 Mbit/ sample	15, 17	Measurements require direct contact with sample and a long duration exposure	Moderate ² / Complex ³
		Mini-Thermal Emission Spectrometer (TES)	2.4	0.3 5.6 peak	TBD	18		
		Alpha proton X-ray spectrometer	0.5	0.4 1.3 peak	16 kbit	15, 17, 19	Measurements require direct contact with sample and a long duration exposure	
		Mini-mass spectrometer	< 5	< 10	TBD	16		
Visual observations for life	organic materials	Gas chromatograph/Mass spectrometer	4.0	8 15 peak	2.5 Mbit max 0.6 Mbit min	15		None/ Simple ¹
		Laser desorption spectroscopy	TBD	TBD	TBD			
		Panoramic stereo camera	2.5	8	8 Mbit/ day	15		
		Imager for Mars Pathfinder	5.2	2.6	TBD	19		

¹Ability to stop and start.

²Ability to stop and start, maneuver in specific directions.

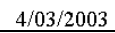
³Ability to stop and start, maneuver in specific directions, point at target.

Appendix B. Balance and Sting Characteristics

Balance 733 Characteristics

Component	Calibration load range		Full scale output (mV/V)	Sensitivity constant		Accuracy, percent F. S. (95 percent Conf.)
	(lb) or (in-lb)	(N) or (Nm)		(lb/mV/V) or (in-lb/mV/V)	(N/mV/V) or (Nm/mV/V)	
Normal	35.0	155.688	1.351	25.9040	115.2269	0.12
	-35.0	-155.688				
Axial	10	44.482	1.250	8.0022	35.5955	0.11
	0	0				
Pitch	50	5.649	1.495	33.4480	3.7791	0.09
	-50	-5.649				
Roll	15	1.695	1.877	7.9901	0.9028	0.09
	-15	-1.695				
Yaw	30	3.390	1.398	21.4517	2.4237	0.08
	-30	-3.390				
Side	10	44.482	1.171	8.5431	38.0016	0.12
	-10	-44.482				

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56

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14. ABSTRACT NASA LaRC is studying concepts for a new type of Mars exploration vehicle that would be propelled by the wind. Known as the Mars Tumbleweed, it would derive mobility through use of the Martian surface winds. Tumbleweeds could conceivably travel greater distances, cover larger areas of the surface, and provide access to areas inaccessible by conventional vehicles. They would be lightweight and relatively inexpensive, allowing a multiple vehicle network to be deployed on a single mission. Tumbleweeds would be equipped with sensors for conducting science and serve as scouts—searching broad areas to identify specific locations for follow-on investigation by other explorers. An extensive assessment of LaRC Tumbleweed concepts was conducted in FY03, including refinement of science mission scenarios, definition of supporting subsystems (structures, power, communications), testing in wind tunnels, and development of a dynamic simulation capability.						
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